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POWDER METALLURGY

Mashgiz

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This book is devoted to an exposition of the methods used in powder metallurgy, the technology of manufacturing metallo-ceramic products, and data on the use of metalloceramic materials.

The book is intended for engineers working in different branches of machine-building and metal-processing industries, for scientific workers, for students in advanced courses at machine- and metallurgical higher technical institutes, and for specialists in the metalloceramic industry.

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Dedicated to the Memory of the
Founder of Powder Metallurgy
Petr Grigor'yevich Sobolevskiy
(1781-1841)

PREFACE

In recent years powder metallurgy, (metalloceramics)
a young branch of technology of extreme importance to present-
day machine-building has been developing at a very fast tempo.
In this connection books on powder metallurgy published either
at home or abroad not only before the war but even 3-4 years
ago are now considerably outdated.

Prior to the war, the low level of development of its
technology and inadequacy of published works presented great
obstacles to the compilation of a book on powder metallurgy.
On the other hand these same conditions made it easier for mono-
graphs to appear which reflected in a most complete way the
condition at the time of the technology of powder metallurgy.

At the present time the scientific and technological
level of powder metallurgy has reached a certain degree of de-
velopment, although that part of the work that remains to be
done in the near future in this connection is considerably great-
er than what has been achieved so far. Present-day literature
on powder metallurgy is already so voluminous that it is diffi-
cult to cover it as a whole in a single monograph and therefore
necessary to select the more essential and interesting data.
For this reason the putting out of a monograph which exhaustively
covers the present state of powder metallurgy would present too

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difficult a problem. It is much more practical to compile a
book aimed at presenting the more essential data to a definite
circle of readers.

The author of the present book has tried to acquaint
wide circles of engineering and technical workers in different
fields of machine building and metal-processing with the methods
and possibilities of powder metallurgy and with the uses of
metalloceramic materials.

At first powder metallurgy as a branch of science and
technology was not broken down into powder metallurgy (manufac-
turing of products), the metallurgy of powders (manufacture of
powders), and powder metallography (the theory of powder metal-
lurgy). At present it is not only possible but necessary to
put out a separate special monography on the metallurgy of powders;
there has already been published a book on powder metallography.
However, a book which is meant not only for specialists but also
for non-specialists in powder metallurgy cannot give an exposi-
tion of the technology of production and the use of metallo-
ceramic materials without acquainting one with the elements of
the metallurgy of powders and powder metallography. For this
reason it has also been necessary to include in the book brief
and far from complete data on the fabrication of powders and on
the theory of powder metallurgy.

The main part of the book was written in 1946. The time of
its compilation and publication coincides with jubilee data on
powder metallurgy. In 1826 our precursors P. G. Sobolevskiy and
V. V. Lyubarskiy set up metalloceramic production for the first

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time in the world. In 1827, 120 years ago, Sobolevskiy pub-
lished the first work to appear on powder metallurgy.

In compiling the book use was made of both our own and
foreign sources which had been published for the most part
prior to December of 1946. Toward the end of 1947, while the
book was in process of being published, there appeared most
interesting works by A. I. Gardin, M. G. Grabino and V. G.
Filimonov, V. S. Mes'kin, P. P. Shipulina, G. M. Vainshteyn,
and B. P. Mitrenin, I. M. Fedorchenko. In connection with this
there were included certain amendments during the proof-read-
ing of the book.

The author considers it a pleasant task, to express his
gratitude to a number of persons who aided him in the compila-
tion of the book. He is especially greateful to Corresponding
Member of AN USSR I. A. Oding, Professor Doctor Ya. S. Umanskiy,
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Candidate Technical Sciences M. K. Rybal'chenko and the editor
Docent M. N. Dunyavskiy.

M. Yu. Bal'shin.

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Chapter I

INTRODUCTION

BASIC CONSIDERATIONS

By powder metallurgy or metalloceramics is meant that branch
of technology which deals with the manufacture of products from
metallic powders.

A fundamental aspect of metalloceramic technology consists
in pressing a proper mixture of powders and in thermal treatment,
so-called baking, of the compacts so obtained at a temperature
below the melting point of the basic component part of the mix-
ture. The pressing is done in steel press molds at a pressure
of 1,000-6,000 kilograms per square centimeter. The baking tem-
perature for the majority of pure metals is 2/3 to 3/4 of their
absolute melting point. The baking of many alloys is often done
at a temperature slightly above the melting point of the most
easily fusible component.

After baking, products generally have a certain porosity
(varying from several percent to 30-40 percent, and in special
cases even as high as 60 percent). An additional processing by
means of compression (cold or hot) of baked products is done in
many cases to decrease this porosity, to improve mechanical
properties and to attain precise measurements. Sometimes there is
also a supplementary heat treating of baked products (such as
cementation). In making carbonyl iron and steels the pressing
operation is not used; instead, non-pressed powders are poured
into the necessary forms and then baked. In other cases, such

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as fabricating porous iron for calking pipes, the baking opera-
tion is not used. Finally, pressing and baking are sometimes
combined into a single operation of so-called hot pressing —
compressing under heat. Figure 1 depicts in the form of a chart
several variations of metalloceramic technology.

The term "metalloceramics" is based on the resemblance of
technological methods in powder metallurgy to those of ceramic
production. In connection with the expression "metalloceramics",
many persons not sufficiently versed in the subject have an
erroneous idea that metalloceramic materials consist of a mexture
of metal with ceramic substances. The term "powder metallurgy"
in its turn evokes an erroneous conception of our specialty as
being a branch of metallurgy. In reality metalloceramics is a
branch not of metallurgy but of metalworking. In our opinion a
more precise and accurate term would be the expression "powder
metalworking". Nevertheless, we make use in the book of the
not-so-happy but widely used terms "powder metallurgy" and
"metalloceramics".

1, 2, 3, 4, 5, 6, 7, 8, 9

(A) Making Up of Powder Mixture

1, 2, 3   4, 5   6   9

(B) Pressing   (B) Pressing   (B) Pressing   (B) Hot Pressing

                    4   5

                Mechanical   Preliminary

                Processing   Baking

                                  6

                               Mechanical

                               Processing

1, 2, 3   4, 5   7, 8

(C) Baking   (C) Baking   (C) Baking

      2   3   8

(D) Later   (E) Saturation   (D) Compression

Treatment   with Molten   Treatment

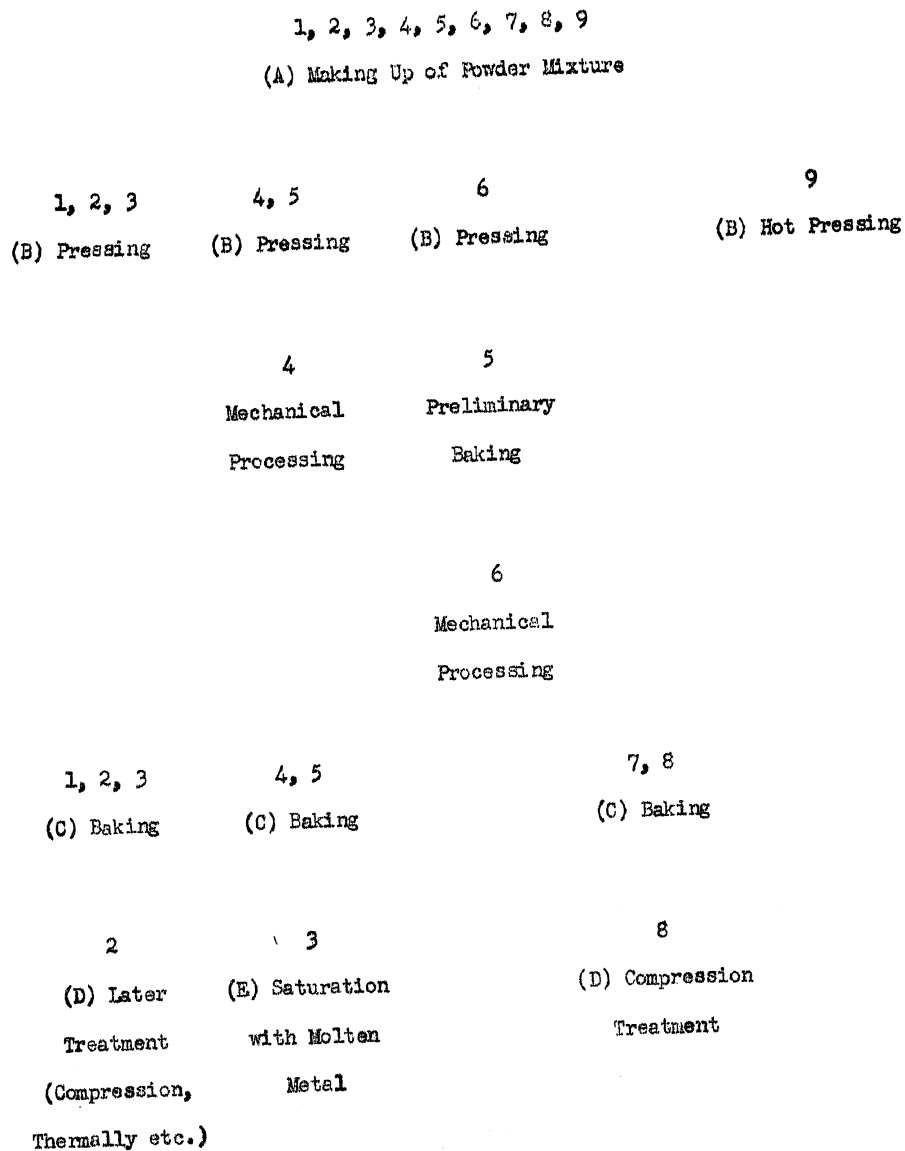(Compression,   Metal

Thermally etc.)

Figure 1. Variations of Metalloceramic Technology:

1 - basic method; 2 - making bearings, details, tungsten, etc.;
3 - obtaining certain contact materials, alloys of iron with
copper, etc.; 4, 5 - production of hard alloys; 6 - omission of
baking (porous iron for calking pipes); 7, 8 - omission of pressing
operation (7 - filters, 8 - carbon iron); 9 - hot pressing
(hard alloys, dimong-metallic compositions).

THE ROLE OF METALLOCERAMIC MATERIALS IN MODERN TECHNOLOGY

The production of metalloceramic products at the present
time is still quantitatively very small -- less than 0.1 percent
of the total production of metals. However, one cannot conceive
present technology without the existence of metalloceramic pro-
ducts.

It is sufficient to point out the following fields of
application. Incandescent filaments for electric bulbs and metal
parts for radio tubes are made from powders of refractory metals
- tungsten, molybdenum, and tantalum by methods of powder metall-
urgy. Copper-graphite brushes for dynamos and electric motors
are also made by means of metalloceramics. The use of cores for
induction coils made from iron powders insulated with plastic has
made it possible to produce easily portable radio sets for tanks
and airplanes. Present metalloceramic hard alloys, introduced
in 1927, have caused a veritable revolution in the processing of
metals by machinery and compression and in mining. The use of
such alloys has made it possible to increase the speed of machin-
ing metals by approximately ten times. Metalloceramic hard alloys

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have considerably widened the field pertaining to the cutting of
materials. At the present time hard-alloy cutters are used
successfully in the machining of alloys having a hardness of 550
according to Brinell. The cruising speed of airplanes has been
increased during a relatively short period from 150 to more than
700 kilometers per hour. However, the landing speed of air-
planes must remain at the former limit because it is impractical
to increase the size of landing fields. In this connection the
problem of finding new effective materials for braking had become
extremely acute. This problem was resolved by producing metal-
loceramic friction materials from copper, tin, lead, and graphite
powders. Metalloceramic friction disks are widely used at the
present time in airplanes, tanks, tractors, autobuses, etc.
Porous metalloceramic bearings resolved a number of difficulties
in those cases where regular lubrication was impossible.
Metalloceramic porous filters made it possible to decrease con-
siderably the size and weight of installations for filtering fuel
and oils for aircraft and automobile engines, for ship and stationary
diesel engines, etc. The methods of powder metallurgy are in
many cases much more practical than others for mass production
of parts. In order to illustrate the importance of powder
metallurgy in machine building today it may be pointed out that
a heavy bomber has more than 4,000 and a present-day automobile
more than 100 metalloceramic parts.

The use of metalloceramic materials is most important in
defense technology. During the last war bullets and shells with
armor-piercing metalloceramic cores were included in the armaments

of all armies (139). These bullets and shells played a not-in-
significant role in the brilliant victories of the armed forces of
the Soviet Union in the Great Fatherland War (13).

Today we are in the era of atomic energy. The obtaining of
atomic energy is inevitably tied to work with radioactive substances
— synthetic or natural. The protection of personnel from the
harmful action of radioactivity remains a most acute problem.
Lead is inadequate for screens and containers which absorb such
radiation because of its relatively low specific gravity (11.3
grams per cubic centimeter) and also because of its inadequate
physical durability. Containers for radioactive materials
are made in England and the US from so-called heavy alloys
(whose specific gravity is about 17 grams per cubic centimeter)
obtained by metalloceramics from tungsten, copper, and nickel
powders.

The examples cited above far from exhaust all fields using
metalloceramic materials in contemporary technology. Types and
applications of metalloceremic products are described in greater
detail in chapters X-XVIII. Here we are limiting ourselves
solely to pointing out the extremely wide diversity of products
made at the present time from metalloceramic materials. Besides
refractory metals, such as tungsten, molybdenum, tantalum,
powder metallurgy has also used easily fusible metals like tin
and lead. The techniques of metalloceramics produce the more
refractory alloys on the case of refractory carbides and the
softest materials, such as highly-porous iron which has the hard-
ness of lead. Powder metallurgy makes it possible to obtain the

most heavy (tungsten, uranium, heavy alloys of tungsten) as well as the lightest metals (berillium, magnesium alloys, porous aluminum). Materials are manufactured from powders which have a wide range of porosity (from 60 percent to zero) and mechanical properties. Thus we can produce at will from iron powder materials which have the characteristics of either iron, bronze, or even lead. Finally, powder metallurgy makes it possible to manufacture a wide variety of materials, such as lead—graphite, metal—plastics, etc. Figure 2 shows a group of metalloceramic parts which give a general idea of the variety in the selection of products that can be produced by the methods of powder metallurgy.

The role of powder metallurgy in technology will doubtless grow even more in the near future. On the one hand, as metalloceramic technology becomes less expensive and more improved, there should be an increase in the competitive value of powder metallurgy in the field of products that are already in existence; on the other hand, technology should make a demand in the near future for new materials in the production of which metalloceramics has definite advantages. Thus it is certain that powder metallurgy will play an important part in the production of heat-resisting materials useful for work in high temperatures (154).

ADVANTAGES OF POWDER METALLURGY

The development of powder metallurgy has been conditioned in the main by two basic advantages of metalloceramic technology, namely:

(1) the possibility of fabricating materials that cannot be produced in the usual way;

(2) the possibility of obtaining materials in the form of ready parts not requiring further machining (Figure 2).

The methods of powder metallurgy made it possible to produce such important materials as refractory metals (tungsten, molybdenum tantalum, niobium), alloys with a high content of refractory metals, compositions of metals which do not mix with each other in the liquid state or which have large differences in their melting points (such as tungsten—cooper, iron—lead), compositions of metals and non-metals (copper-graphite, iron—plastic, metal—diamond); porous metals (bearings, filters), etc. Powder metallurgy is the exclusive method for their manufacture, inasmuch as such materials cannot be obtained ordinarily. Metalloceramics in this way makes it possible to produce new industrial materials. The advantages of powder metallurgy may be illustrated graphically by citing present-day metalloceramic hard alloys based on tungsten carbide (92-94 percent tungsten carbide WC and 6-8 percent cobalt). Such alloys are sintered at 1,400 degrees.

Figure 2. Various Metalloceramic Products.

A temperature of 3,000 degrees would have been required to make them by casting methods. Moreover, because of coarseness, defects of casting (of pouring or mold), and the splitting of tungsten carbide WC into W_2C and graphite, the quality of castings

of hard alloys is many times inferior to those of metalloceramics.
Resistance of hard-alloy castings to bending (20-30 kilograms per
square millimeter) is 5-6 times less than for metalloceramics
(120-180 kilograms per square millimeter). Finally, metalloceramic
hard alloys are produced in the form of finished plates which do
not require further machining and which for such cases would
present exceptional difficulties.

Powder metallurgy makes it possible to obtain finished
products (Figure 2) which do not require further machining with
third or second, and, in some cases, first degree of precision.
This factor makes for a number of important economic advantages --
speeding up of the process of fabricating parts, reducing working
time, releasing a considerable percentage of metal-working
machines and decreasing capital expenditures, through no loss
of metal to chip formation, which amounts to 20-80 percent of
the weight of the metal by other methods. Metalloceramics today
is successfully competing with other methods of fabricating many parts
from nonferrous and ferrous metals.

Powder metallurgy results not only in a quantitative eco-
nomy of metal (no loss to chip formations use in certain cases of
light porous metals, and longer durability) but also a qualitative
one (use of substitutes). It has been pointed out above that
there can be produced from iron powder a metal possessing not
only the chracteristics of ordinary iron but also of bronze or
even lead.

There can thus be obtained from ordinary iron materials

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with new technical characteristics allowing bronze to be replaced in bearings, copper in shell collars, or lead in calking joints of water pipes.

In addition to the already cited advantages of powder metallurgy, a few others may be added. Powder metallurgy makes it frequently possible to obtain with greater ease pure metals and alloys of a given chemical composition. In cast metals there is inevitable a certain contamination through the admixtures of reducing agents and materials used for lining furnaces and crucibles, etc. When baking metal powders, one can obtain in the proper gaseous medium such high-quality metals and alloys as iron, nickel, alloys of iron, nickel, molybdenum and cobalt, etc. for use in vacuum technology (167).

Metalloceramic technology makes it possible in a number of cases to more easily control structure and mechanical properties than with the ordinary methods. Thus, it is difficult to obtain a fine-grained structure and satisfactory mechanical properties for cast magnetic alloys of the type of alnico (iron, aluminum, nickel, cobalt) (167) or cast berillium (166). Powder metallurgy makes it possible to produce such materials with a fine-grained structure and with satisfactory mechanical properties.

LIMITATION FACTORS IN THE APPLICATION OF POWDER METALLURGY

Together with the advantages of metalloceramics one should remember its disadvantages. These should be considered (176) as

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factors that limit the application of powder metallurgy.

The following may be considered to be its principal defects:

(1) The relative high cost of metal powders. In certain cases
(such as the reduction of casting "skin"), the manufacture of powders
is tied to considerable capital expenditures. However, considera-
ble success has been recently achieved in lowering manufacturing
cost of powders and decreasing capital expenditures.

(2) The difficulty of obtaining certain metals and alloys
by means of metalloceramics, particularly metals which form oxides
difficult to reduce, or metals with a high rate of evaporation
at baking temperatures (such as aluminum, zinc, alloys with a
high content of silicon or chromium). However, these difficul-
ties are being successfully overcome through technical develop-
ment. Thus, 10 years ago it was considered impossible to produce
aluminum and alloys with a high content of aluminum through the
use of methods of powder metallurgy.

At the present time metalloceramic products made from
aluminum and its alloys are being produced on an industrail scale.
Production of alloys with a considerable content of zinc (brasses),
chromium (stainless steels), etc., has been established in the
same way.

(3) Limitations as to dimensions of metalloceramic parts
both as to size and as to form in connection with the specific
difficulties involved in pressing metal powders. However, the
choice of products that are being manufactured is increasing each
year because of swift progress in the technology of pressing.

Five years ago the size of metalloceramic parts was limited approximately to 150 millimeters in height and diameter. At the present time bearings are being made that have a diameter of 450 millimeters and a weight of 50 kilograms, plates longer than 3 and 1/2 meters, ingots weighing 2 tons, parts of such complicated structure as gears, separators for ball bearings, etc. (see Figure 2).

(4) The need for baking in a reducing or protective atmosphere because of the higher oxidizability of metal powders as compared with compact metals.

(5) The unprofitability of producing items of individual size manufactured in small quantity. The production of such products to precise dimensions is unprofitable because of the high cost of press molds. Subsequent machine tooling of metalloceramics is also unprofitable because of the considerable amount of powdered metal lost to chip formation.

It has been pointed out above that the difficulties of metalloceramic technology are being overcome by technological progress, as a result of which the application of metalloceramic materials is widening.

However, it should be kept in mind that successes in other branches may on the other hand render valueless the positive features of metalloceramics in making certain materials and thereby limit the application of powder metallurgy. Thus 120 years ago powder metallurgy was a method which practically held a monopoly in the production of malleable platinum (see below).

Today progress in high-temperature technology has caused powder
metallurgy to yield its place to the usual methods of smelting
and casting.

A FEW HISTORICAL FACTS

It is sometimes said that powder metallurgy is "as old as
the pyramids and as new as the present-day bomber". Some truth is
to be found in this witticism.

Many authors (154, 167, 194) consider the precursors of
powder metallurgy to be the methods in manufacturing steel pro-
ducts that have been used many thousands of years ago. In redu-
cing iron ore through the use of coal in primitive hearths in
ancient times it was impossible to achieve a temperature capable
of melting the iron. For this reason products were made by
hammering hot pieces of reduced iron. This method, which had
been used 1,600 years ago in India for making columns weighing
6 1/2 tons for the temple at Delhi, existed at the very least
3,000 years before our era.

There are a number of instances on record of the use by
ancient peoples of precious metal powders. Thus inscriptions
found in the tomb of the Egyptian pharoah Tutankhamen (194)
point out that the handles of daggers preserved in the tomb
were embroidered with powdered gold. According to the findings
of Bergso (194), long before the discovery of America by
Columbus the Incas manufactured products by baking powders of
platinum 26-72 percent, gold 16-64 percent, silver 3-15 percent,
copper up to 4 percent.

However, all these materials were made not by the present-day method of baking powders that had first been compressed, but by hot forging of a baked powder mass. Credit for the first industrial application of present-day methods of powder metallurgy belongs to the scientist P. G. Sobolevskiy (13, 51, 79, 110, 111, 112, 113, 123, 132).

[Picture]

P. G. Sobolevskiy

(1781-1841)

Petr Grigor'yevich Sobolevskiy, the son of Grigoriy Fedorovich Sobolevskiy, a professor of botany at Petersburg University, was born in 1781. In 1824 he was decorated with the Order of Vladimir, 4th degree, "for his care and labors leading to the actual construction of the 'hermolamp' which up to now had not existed in Russia." In 1826 Sobolevskiy was appointed "ober-berg-probirer" [chief essayist] of the Amalgamated Laboratory of the Department of Mining and Salt Affairs and the Mining Cadet Corps and was assigned the problem of evolving a method for obtaining pure platinum.

It was not known at that time how to produce temperatures high enough to melt platinum (melting point 1770 degrees). For this reason it was necessary to use the indirect method of Akhard (133) for obtaining platinum. Arsenic was added to platinum to lower its melting point. The arsenic was later removed by a prolonged oxidation annealing. Sobolevskiy (110) described the defects of Akhard's method in the following manner.

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"The prolonged duration of this method, requiring several days to burn out a pound smelt of platinum, the grievous harm that could result from arsenic fumes both to workers and to persons living in the neighborhood, and, together with this, its unreliability for with all our attempts and the efforts of the foreman Sysoyev, we could not obtain a satisfactory piece of platinum larger than 28 zolotniks, -- all these factors together forced us to abandon such an unreliable method and to try to find another more reliable one. Our efforts were not in vain. We soon found ourselves quite happy to learn that our desire to fulfill the wishes of our solicitous superiors was met with complete success ..."

The method developed by Sobolevskiy from 12 to 24 May 1826 with the help of Vasiliy Vasil'yevich Lyubarskiy (born in 1795, died in 1852) consisted of the following. Platinum powder, obtained by calcination of ammonium chloroplatinate, was pressed into cylindrical ingots, which, after baking, were subjected to an additional heat treatment by compression. This is how Sobolevskiy himself described his method (110).

"This method consists of the following: we beat the purified aluminum in its spongy condition while it is cold quite compactly into an iron ringshaped mold of arbitrary size, compress it with determined action by means of a screw press, and then, upon removing it from its mold, we have a solid disk with a metallic luster.

"The platinum disk in this condition has yet no ductility,

while the cohesion of its particles with respect to each other can-
not resist hard blows; it simply breaks and crumbles. In order
to transform such disks into malleable platinum, it is only neces-
sary to heat them to white heat and, at this degree of heat, sub-
ject them to the pressure of the same press. One blow is suf-
ficient to cause the platinum disk to completely change its state;
its granular structure becomes compact and it becomes completely
malleable. The size of a disk makes no difference in any case, a
large or small disk, upon receiving a single blow, becomes evenly
malleable and ductile.

"Following this compression the disks are forged into
strips or rods of the desired shape in the usual way ... "

As can be seen from Sobolevskiy's description, this method
is no different in principle from contemporary methods of obtain-
ing compact metalloceramic materials.

On 21 March (2 April) 1827 there took place a reading of
the description of the work of Sobolevskiy and Lyubarskiy at a
grand session of the Learned Committee, Mining and Salt Division.
There were exhibited tokens, medals, ingots weighing 6 pounds, wire,
cups, and crucibles. In the same year Sobolevskiy made public
his work in the <u>Mining Journal</u> (110). The Treasury began to sell
platinum produced by Sobolevskiy's method in ingots, sheets, and
wire already in the spring of 1827 at a cost of 5 rubles per
zolotnik. On 19 August 1827 Nicholas I approved the drawings
for the stamping of platinum coins, while on 24 April 1828
there was made public a decree for stamping "a limited number"

of platinum coins. Three-ruble coins were minted having a content of 2 zolotniks possessing 41 parts of pure platinum.

The Government highly appreciated Sobolevskiy's services. In 1829 a letter by the Minister of Finances Kankrin showed that he was to receive above his regular salary a sum of 2,500 rubles annually "As long as he remains in service". In 1830 Sobolevskiy was chosen as Corresponding Member of the Academy of Sciences.

Sobolevskiy died suddenly in Petersburg on 24 October 1841.

A similar method for obtaining platinum by pressing and baking was made public in England by Wollaston (195) in 1829, three years after Sobolevskiy had completed his work. Certain foreign authors credit Wollaston with having been the first to develop contemporary metalloceramic technology. However even they cannot deny the obvious fact that the first industrial application of powder metallurgy belongs to the work of Sobolevskiy. Thus Smith (194) writes that the minting of platinum coins by Sobolevskiy's method "evidently was the first industrial application of baking at high temperatures of powders that had first been compressed in distinction to earlier methods of hot pressing". Kiefer and Cotop (167) also point out that: "As far as it is possible to establish, platinum coins put out in 1826 by the Russian Imperial Mint were the first industrial application of powder metallurgy."

The making of platinum coins by means of powder metallurgy in Russia was carried on for 18 years, being stopped in 1846 by the Edict of 22 June 1845. During this time there were minted

coins to the amount of 4,25.,843 rubles. An interesting descrip-
tion of the technology of production of metalloceramic platinum
was published in 1843 by Kovan'ko (57).

The preparation of platinum by powder metallurgy methods
was discontinued abroad in 1859 when St.-Clair-Deville began to
apply heating by oxygen-hydrogen flame for smelting platinum. (194)

Powder metallurgy after this was basically forgotten (if one
does not consider the preparation of dental fillings from mercury
amalgams of precious metals developed in 1855).

Powder metallurgy was again remembered only at the end of
the 19th century in connection with the fabrication of metal
incandescent filaments for electric bulbs. (Consider ble histori-
cal information on the production of incandescent filaments for
electric bulbs may be found in A. P. Ivanov's book Electirc Bulbs
and Their Manufacture (Elecktricheskiye lampy i ikh izgotovleniye)
(52). The hard-alloy metal osmium was the first to be used for
this purpose. Present-day methods for fabricating drawn tungsten
filaments were developed about 1910.

Since then powder metallurgy has found consistent applica-
tion in the electrical industry. Further progress of metalloceramics
is also closely tied to this branch of industry.

Almost at the same time that metalloceramic incandescent
filaments came to be used, metalloceramic copper-graphite brushes
for dynamos and electric motors also were adopted (1900-1905).
During 1917-1921 there were developed methods for fabricating
contact metalloceramic materials (tungsten-copper, tungsten-silver
etc.). The production of cores for induction coils from iron powder

was begun during the time of the First World War. Present-day
methods for fabricating magnetic cores from iron powder were de-
veloped during 1919-1921.

It is interesting to note that the electric bulb industry
also stood at the cradle of present-day metalloceramic hard
alloys. The process of drawing hard tungsten wire put very great
demands on the material of the wire draw plate. At that time
only diamond could meet these requirements. The first attempts
to replace diamonds by cast tungsten carbide were made in the
beginning of the 20th century. Then because of the difficulties
connected with obtaining cast carbide and its unsatisfactory
quality, tungsten carbide came to be produced by powder metal-
lurgy methods. The mechanical strength of baked pure tungsten
carbide was inadequate. Therefore in 1922 there came to be
added a small quantity of cobalt to tungsten carbide as a sticky
cementing metal. This served as the foundation for fabricating
present-day hard alloys (167).

As early as 1909 there was proposed the use of porous
metalloceramic products for use as filters, bearings, etc.
However, porous bearings came to be used on an industrial scale
only about 1924 (194). The first porous bearings were fabricated
with tin bronze to which graphite had been added as a base. In
the 1930's porous bearings came to be made with iron as a base.

One of the first uses of ultrasoft metals was highly
porous iron replacing lead, as proposed in 1935 by Bal'shin,
Borok, and Ol'khov (15). In 1936 porous iron was used for
calking joints of pipes in place of lead.

After 1936 there was started mass production of different small
parts (see Chapter XVI) from iron and nonferrous metal powders.
During the war this production greatly increased and now is suc-
cessfully competing inmany cases with the usual methods of
producing parts.

During the war, metalloceramic amorpiercing bullets and
shells (139), shell collars (152), etc., were used widely.

The production of gold and silver powder for decorative
purposes was known to ancient peoples and is described in a number
of manuscripts. One of the first manuscripts translated into
French by Bertello was written in Egypt more than 3,000 years
prior to our era. The manufacture of these powders was described
by Heraclius in a manuscript De coloribus et artibus Romanorum,
by the Monk Theophile in the 11th century, by Alessio Piemontese
in 1555, etc.

The first factory manufacture of brass and bronze powders
for decorative purposes was established about 100 years ago in
England by the well-known metallurgist Henry Bessemer. It is
interesting to note that the profits made by Bessemer from this
manufacture (300,000 pounds sterling) served as the foundation
for his wealth and made it possible for him to work upon the
invention of the Bessemer convertor.

Of very great importance in the preparation of metalloceramic
products was the vorticity-mill method of grinding developed
about 1930 (see Chapter II).

One may note the following facts applying to the development
of powder matallurgy.

(1) In the history of metallurgy the golden age preceded the bronze, and the bronze the iron. In exactly the same way is it true of powder metallurgy, for the precious and rare metals were obtained prior to nonferrous, and nonferrous prior to ferrous.. At the present time the emphasis in metalloceramic technology is to be found more than anywhere else in the metallurgy of rare metals. Metalloceramics enjoys a practical monopoly in the manufacture of rare refractory metals and alloys with little waste. A smaller proportion of metalloceramics is to be found in the metallurgy of nonferrous metals and a still smaller one in the metallurgy of ferrous metals.

(2) Metalloceramics was first used for obtaining such materials over which it exercisezed a monopoly. Only recently have improvements and decreases in costs of its technology made it possible for it to compete with the usual methods for the manufacture of metal products.

THE SCIENTIFIC FUNDAMENTALS OF POWDER METALLURGY

Metal powders whose particles vary in size from 0.1 microns to several millimeters occupy a middle position according to the degree of division of matter into structural elements between colloids having particles smaller than 0.1 microns, and solid bodies larger than several millimeters in size. With respect to the degree of cohesion of structural elements, powders also occupy an intermediate position between colloids and solid bodies. Colloidal particles are isolated from each other by an intermediate medium. The granules (crystallites) of solid metals are

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characterized by full (or almost full) mutual contact. The contact areas occupy only a small part of the surface or particles is separated by space or, as it is usually termed, pores.

From the scientific point of view the operation of fabrication from powder of metalloceramic products may be reduced to increasing contact among the particles. Increase in contact may be achieved in two ways — by deformation of particles through the use of external forces (pressing, calibrating) or by drawing the atoms of a metal closer together through increased temperatures. Powder metallurgy in practice uses both ways in one or another combination for the fabrication of products. Simultaneously with an increase of contact between the surfaces of particles there is an increase in the strength and cohesion of the metal powder.

In this connection, in the development of the scientific fundamentals of powder metallurgy, the study of contact phenomena is of great importance. The primary problems of powder metallography are to establish the following correlationships.

(1) How is the contact surface of particles of a metal powder modified during deformation (pressing, calibrating) and in thermal treatment (baking).

(2) How does the structure and mechanical properties of the powder metal change in relation to the size of contact surface between its particles.

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Chapter II

METAL POWDERS

A. METHODS OF OBTAINING METAL POWDERS

The method to be used determine both the economics
(cost of powder, size of capital investment, cost of transfor-
ming a powder into a finished product) and the qualitative charac-
teristics of a powder (content of admixtures, size and shape of
particles, pouring weight, compressibility and sintering
characteristics of the powder, etc.).

For this reason the selection of the method to be used in
obtaining a powder is of paramount importance. Today the tech-
nology of metalloceramic manufacture is on such a high level that
it is now possible to use it directly to obtain products from
both cheap and low quality materials (steel and iron shavings).
Further progress of powder metallurgy, just as in all other
branches of technology, doubtless will follow the line of de-
creasing the cost of initial materials and of the technology of
their processing. Thus economic factors will have to play an
important role in the selection of methods for fabricating powders.

Table 1 gives a short resume of the different methods used
in obtaining powders. Of greatest importance are the following
methods which are least expensive in fabricating powders: (1)
mechanical comminution of hard metals, (2) pulverization of
liquid metals, and (3) reduction of oxides. Electroylysis is
also widely used in a number of cases, although it usually is less

economically feasible than the three methods just outlined. There
are other methods which are important either for certain special
cases (such as the preparation of magnetic alloys from carbonyl
iron and nickel) or are only of scientific interest (obtaining
powders by electro-erosion of metals), in the present state of
technology.

Mechanical Comminution of Hard Metals

The following possible ways exist for mechanical com-
minution of metals and alloys in a solid state:

(a) Processing of metals by machining.

(b) Crushing metals with ordinary equipment (ball and hammer
mills, crusher rollers, etc.).

(c) Comminution of metals in vorticity mills.

TABLE 1

BASIC METHODS FOR OBTAINING METAL POWDERS

[1] Original Material	[2] Method Used	[3] Product to be Made	[4] Shape of Particles	[5] Size of Particles in Microns	[6] Fields of Application
A. Hard metals and alloys	I. Mechanical Comminution 1. Treatment by mach ning: Utilization of waste from metal processing by machin- ing (shavings) for later pulverization into powder in ball, vorticity, and similar mills. Small sha- vings may be used directly in the fabrication of metal-	Iron, steel, slight- ly siliceous iron, brass bronze, etc.	Acicular, curled, etc.	1,000-10,000	Original material for further comminu- tion, as well as for porous bearings, steel parts, etc.

[1]	[2]	[3]	[4]	[5]	[6]
	loceramic products (4, 7, 8, 167, 194).				
	2. Comminution in ball mills, crusher rollers, etc.				
	(a) Pulverization of brittle metals and alloys (4, 8, 167).	Ferro-alloys, white iron Mn, Cr, Sb, Bi	Irregular po- lyhedrons	10-100	Steel parts, metal- loceramic iron, for chemical uses, etc.
	(b) Pulverization of un- stable accumulations of malleable metals (brittle electrolytic sediments, reduced iron sponge) (4, 8, 167).	Fe	Depending on the form of the pulveri- zed partic- les	10-100	Cores of induction coils, porous bear- ings, etc.

[2]	[3]	[4]	[5]	[6]
(c) Spcial alloys made brittle by the addition of admixtures and special treatment (4, 8, 167).	Permalloy (Fe-Ni)	Irregular po- lyhedrons	10-100	**Magnetic materials**
(d) Coarse Pulverization of malleable materials with weakened cohesion between its gra- nules (shavings) (4, 8, 167).	Steel, brass, etc.	Leaves, coils, etc.	100-3,000	Porous bearings, steel parts, etc.
3. Vorticity comminution Ductile metals and alloys, brittle metals and alloys (4, 8, 34, 167).	Fe, Fe-Ni, Cu, Ag, Al, Ag-Sn, etc.	Disk-like, with flanged edges	24-400	Porous bearings, cores, electric brushes, dental fillings, etc.

[1]	[2]	[3]	[4]	[5]	[6]
	II. <u>Physico-chemical Commi-nution.</u> 1. Chemical comminution. Inter-crystallite corrosion of stainless steel 18-8 (194).	Stainless steel	Irregular po-lyhedrons	10-100	Stainless steel parts
	2. Electro-erosion (67).	Hard alloys and all possible kinds of other metals			Scientific research work
B. Metals and alloys (primarily easily fusi-ble) in li-quid state	I. <u>Granulation and Pulveriza-tion</u> 1. Pouring into water (4, 8, 14, 69, 34, 167, 81).	Pb, Fe, Cu, Ag	Spherical	100-500	Porous bearings, elec-tric brushes, filters, magnetic materials, parts connections, dental fillimg, etc.

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[1]	[2]	[3]	[4]	[5]	[6]
	2. Mixing alloys while hardening (167).	Alloys of Al, Cd, Sn, Zn	Irregular, granular	250	
C. Metals and alloys (primarily easily fusible in liquid state	3. Pulverization by air and steam (4, 8, 54).	Al, Cu, Fe	Irregular drops	20-400	
	4. Pulverization with simultaneous mechanical action (14, 167)	Fe, Cu, Ni, Al, bronze, copper, Cu-Pb, Cu-Ag, etc.	Irregular broken up drops with complex outlines	20-400	
C. Metal combinations	I. Condensation of metal Vapors (4,167).	Zn	Spherical	0.1-10	Chemical Processing brass parts, hard alloys, etc.

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[1]	[2]	[3]	[4]	[5]	[6]
D. Metal combinations	I. Reduction 1. Reducation of solid compounds (oxides, ores, organic salts) with hydrogen, carbon and their combinations (4, 167).	W, Mo, Fe, Ni, Co, Cu	Sponge-like	0.1-30	Electric bulb industry, coating of high temperature furnaces, contact, hard alloys, porous bearings, magnetic materials, etc.
	2. Reduction from liquid solutions of salts (4, 167).	Ag, Au, Cu, Pt, Sn, Ni, Co	Varying (Needlelike tablets, poly hedrons)	0.1-10	Porous bearings, contacts hard alloys, etc.
	3. Reduction of melted salts with alkaline and alkali earth metals (4, 99, 167).	Ta, Nb, Ti, Th, Zr, V, U	Varying	0.1-10	Draw plates, vacuum and chemical industiries, etc.
	II. Thermal Dissociation Splitting up of carbonyls (4, 21, 167).	Ni, Fe	Spherical	0.1-5	Magnetic materials, vacuum industry, pure alloys, etc.

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[1]	[2]	[3]	[4]	[5]	[6]
	III. Electrolysis 1. Water solutions (4, 21, 167).	Fe, Cu, Pb, Sn, etc.	Dendrite	0.1-30	Porous bearings, brushes, contacts, magnetic materials, etc.
	2. Melted media	Ta, Nb, Ti, Th, Zr, V, U	Dendrite	0.1-10	Draw plates, vacuum industry, chemical industry, etc.
E. Metal and nonmetal powders	I. Obtaining powders from metal comounds and alloys as a result of diffusion and chemical reaction due to heating (19, 99, 167).	Refractory carbides, borides, nitrides, brass, etc.	Varying	1-100	Hard alloys, refractory compounds nonferrous alloy products, etc.

Mechanical pulverization methods are widely used for obtaining powders from different metals and alloys.

(a) The Machining of Metals by Cutting

It is economically unfeasible to specially produce shavings for immediate use in fabricating products. However, the use of waste shavings obtained from the processing of metals by Machining is without doubt a much moreprofitable undertaking for further comminuntion in ball, hammer, or vorticity mills. Small shavings of iron, steel, or steel-like slightly siliceous iron containing up to 1.5 percent of silicon with particles about 1 millimeter in size (shavings from drilling, cutting, and even finish lathework) may be used directly without any preliminary comminution in fabricating products.

(b) Comminution of Metals with OrdinaryEquipment (Ball Mills, Hammer Mills, Crushers, Rollers, etc.)

In such cases metals are comminuted (crushed and pulverized) by coming into contact with a heavy body or bodies (steel balls, mill stones, rollers, etc.). The weight of all such bodies considerably exceeds the weight of particles obtained through pulverization (at the very least by several thousand times and frequently by many million times). For this reason such a method is useful only for pulverizing brittle metals (ferro-alloys, a number of special alloys, white cast iron, etc.). For ductile metals it results not in pulverization but in a flattening-out of the particles, and for that reason it should not be used for them. In pulverizing ductile metals grinding of this sort may be used

in only a few cases as enumerated below.

(1) Pulverization of brittle and loro-strength agglomerates of particles as a final operation following other methods for obtaining powders (crushing of reduced sponge iron, pulverization of brittle electrolytic iron deiment).

(2) Pulverization of ductile metals with weakened cohesion between granules. For example, one can coarsely pulverize metal shavings in ball and hammer mills by facturing weakned places of cohesion.

Further and finer pulverization does not lead to any useful results.

(3) Pulverization of ductile metals that have been made brittle artificially. For example, pulverization of permalloy (alloy of iron and nickel) is made easier by an admixture of an insignificant quantity of sulphur.

A weakness to be found in working with ball mills, etc. consists sometimes in being contaminated by powders products of abrasion from the steel balls and the lining of the mills. For example, pulverizing powders of hard alloys in ball mills causes them to acquire 1-2 percent of iron.

Figure 4. A Ball Mill.

Figure 4 shews a ball mill for pulverizing powders.

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(c) Comminution by Means of Vorticity Mills

Figure 5 (drawing) and Figure 6 (photograph) show an eddy mill (34). It consists of a casing lined with durable manganese steel in which two propellers are rotated at a high speed (3,000 revolutions per minute) in opposite directions to each other. The material to be pulverized is introduced into the mill in the shape of coarsely comminuted pieces, — cuttings of wire, shavings, etc. These pieces collide with each other at great speed in the eddying currents and break up into particles measuring from 0.02 to 0.3-0.4 millimeters.

Figure 5. Diagram of a Vorticity Mill

The mill has an attachment for air sorting of powders according to the size of particles.

In order to prevent the powders from overheating during pulverization the casing is equipped with a water jacket and is cooled by running water. The mill has a protective air feedline to be used in case of emergency.

The pulverizing agents in a vorticity mill are the actual particles of the metal which is being comminuted through collision. This carries with it two advantages. On the one hand, the powder is not contaminated by metal from pulverizing agents (such as steel balls). On the other hand, the comminution resulting from the collision of light particles does not produce flattened, smooth-surfaces but primarily surface deformations which increase the

roughness of the particles. Thus, the quality of the powder improves with the roughness of the surfaces and is higher than by pulverization in ball mills.

The structure of iron powders obtained by vorticity pulverization is shown in Figure 7. The particles have a characteristic shape of saucers with bent edges.

Table 2 gives a characteristic screen analysis of iron powder resulting from vorticity pulverization.

Table 2

TYPICAL SCREEN ANALYSIS OF IRON POWDER PRODUCED BY VORTICITY COMMINUTION

Size of Particles in Millimeters	Weight of Fraction in Percent
>0.3	4
0.15-0.3	44
0.1 -0.15	12
0.075-0.1	14
0.06-0.75	21
0.05-0.06	2
< 0.05	3

In order to improve the compressibility of such powder and to eliminate cold hardening, it is necessary to subject them to a preliminary heating in a protective atmosphere (iron powder - 1-2 hours at 800-1,000 degrees).

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The productivity of a vorticity mill having a 20 kilowatt motor is about 7-10 kilograms per hour (depending on the fineness of the powder). The amount of electricity used to produce 1 kilogram of powder is 2.5-3 kilowatt hours. O_ne worker can service several such mills simultaneously. Servicing personnel do not have to have particularly high qualifications.

The principal merits of vorticity comminution consist of the following: (1) simplicity and inexpensiveness of the equipment and small capital investment needed to manufacture the powder; (2) inexpensiveness of raw material and the possibility of utilizing waste products from the metalworking industry (shavings); (3) insignificant labor and power expenditures for producing the powder; (4) Simplicity of operation and the possibility of using unskilled personnel; (5) easy control of the process; (6) good adaptibility of powder for compression (after heating) and baking; (7) resistance of powder to oxidation when being stored; (8) possibility of obtaining powder with an insignificant content of foreign matter (absence of contamination during comminution); (9) possibility of obtaining powders from alloys; (10) indentical adaptibility of this method for the production of either coarse or fine powder.

Figure 6. A Vorticity Mill.

Figure 7. Iron Powders Obtained by Vorticity Pulverization Magnified 25 times (167).

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The eddy pulverization method should be given preference in the preparation of iron powder for manufacturing porous bearings, steel parts, etc.

Recently the design of the eddy mill has been somewhat simplified and improved over the one shown in Figure 5. In these models the flow of air issues from the centrifugal blower into the mill casing and is broken up by the dashers; both the dashers and the blower are mounted on the same shaft (34).

In this is to be found the advantage of the new design over the old design, where the propellers were set up on two axles rotating in opposite directions. Moreover, the making of dashers is simpler and costs less than the making of propellers for mills of the previous design.

After pulverization the powder is annealed to remove the cold hardening. The baked mass is first broken up by hand crushers and then with hammer crushers (Figure 8).

Figure 8. A Mill for Breaking Up Powder after Annealing

Granulation and Pulverization of Metal in Liquid State

The comminution of metal in a liquid state is aplied principally to relatively easily-fusible metals—to tin, lead, zinc, aluminum, copper, and their alloys. However, these methods are also used for obtaining powders from iron, pig iron, and steel.

The different variations of comminution liquid metal can be reduced to granulation by pouring into water and pulverizing while pouring it on a fast rotating disk, or by a jet of compressed air or steam, as well as by combination of these methods.

Most interesting is centrifugal pulverizing (34) which combines the pulverizing of the liquid metal with mechanical action on the particles.

1 - molten metl

2 - water under pressure

3 - rotating disk

Figure 9. Diagram of Centrifugal Pulverization.

The basic idea of atomizing by this method is shown in Figure 9. A thin stream of the molten metal issues from a nozzle surrounded by a water jacket into which water flows under pressure. The flow of water carries along with it the metal onto the rotating disk, which is especially designed by being supplied with special fittings for breaking up the powder into small particles.

The shape of the particles of iron powder obtained in this way is shown in Figure 10. The particles have a rough outline. Their size varies from 20 to 400 microns. A typical screen analysis of this powder is given in Table 3.

Figure 10. Iron Powder Obtained by Centrifugal Pulverization
Magnified 20 times (167).

Table 3.

TYPICAL SCREEN ANALYSIS OF IRON POWDER OBTAINED BY CENTRIFUGAL

ATOMIZING (167)

Size of Particles in Millimeters	Weight of Fraction in Percent
0.3	4
0.15 – 0.3	28
0.1 – 0.15	5
0.075 – 0.1	5
0.06 – 0.075	39
0.05 – 0.06	10
0.05	9

The following method is practiced in obtaining iron powder
(181). Molten cast iron with a slight silican content used for
producing steel (0.4-0.5 percent Si), containing up to 4.5 percent
carbon, is poured into water and onto the rotating disk creating
granules up to 4 millimeters in size. These granules are then
subjected to a decarbonizing annealing in a rotating furnace at a
temperature of approximately 1,000 degrees in an atmosphere con-
sisting of $CO-CO_2$. A load of 100 kilograms of granules in an
oven with an annealing temperature of 1,040 degrees produces a carbon
conten of 0.03. This process is used for later smelting of

decarbonized granules. However, the smaller granules (up to
0.5 millimeters), which make up about 40 percent /of the powder/,
can be used for meeting the needs of powder metallurgy.

Pulverization is achieved in other cases by directing com-
pressed air on a molten charge to which coke dust has been added
(34). The atomized powder contains about 6 percent O_2 and 4
percent C, thanks to which it is completely reduced in its "own"
reducing atmosphere at an annealing temperature of 900 degrees.

REDUCTION OF OXIDES

The reduction of oxides in metal powders is from the theore-
tical point of view is one of the most profitable ways of producing
metal. However, in reality the producing of pig iron by means of
the open hearth process followed by later processing of it into
wrought iron is more practical than direct reduction of ore
because of severe difficulties existing at the present time in
connection with equipment.

Metalloceramic manufacture demands relatively pure powders,
inasmuch as the greater part of an admixture is carried along
into the finished product. The degree of purity of reduced
powder is determined by the contents of impurities in the ori-
ginal oxides. For this reason, because of the exacting demands
of industry, pure original materials are used which have been re-
duced by means of hydrogen. The reduction of the oxides with
hydrogen proceeds according to the equation (for simplicity we have

taken a bivalent oxide):

$$MeO + H_2 \rightleftharpoons Me + H_2O.$$

Where requirements are lower for a product and where the possibility exists for concentration, less pure original materials may be used (such as iron slag) with reduction being carried on in a generator gas, illuminating gas, or hard carbon.

The reducing power of oxides considerably increases with an increase in porosity and dispersion of the particles of the original oxides. Oxides created synthetically, especially if through chemical means, are more porous and dispersed than natural ores or slag, and for that reason are reduced at lower temperatures.

along AA

A

Condenser   A

Figure 11. Electrical Resistance Furnace for Reducing Tungsten

Reduction is practically the only way to produce tungsten and molybdenum powders.

The oxides of ores which are obtained in chemical treatment are porous and most dispersed (the size of particles is on the order of 1 micron or less) and are reduced at a relatively low temperature (about 800 degrees).

Tungsten and molybdenum used in electric bulb manufacture are reduced by hydrogen in tubular furnaces. Figure 11 shows an electrical tubular resistance furnace. Metal boats containing the raw material are inserted into the furnace, which then are passed through the variable temperatures of the heated section. After reduction, the boats are moved into the condenser where they are cooled by circulating water. They are placed into the furnace at fixed intervals of time. Upon loading the next boat following is moved forward the length of one boat. There generally is a series composed of several such furnaces. The hydrogen issuing from the furnace passed through a hygroscopic device on its way into the next furnace. The hydrogen is burned as it comes out of the last furnace.

Especially pure tungsten is not required for the production of hard alloys, and for such cases it is reduced with carbon black in furnaces, a picture of which is shown in Figure 85.

Cobalt and nickel used in the manufacture of hard alloys are also obtained through the reduction of dispersed oxides.

A much more difficult problem is to be found in the economic reduction of iron powders. From the economic point of view only cheap original material can be used in reduction — separated crushed slag of steel with low carbon content, which can be restored only in high temperatures (1,000-1,100 degrees). The reduction of the slag is carried out in tubular furnaces of the same type as shown in Figure 9 but which are heated by generator or illuminating gas (61). Reduction is done in an atmosphere

of generator or converted illuminated gas. Considerable diffi-
culty is presented by the frequent change of metal tubes.

a

b

Figure 12. Reduced Iron Powder.
a - Before pressing; b - After pressing.
500 X (Bal'shin).

Reduced powders have a characteristic spongy structure
in which individual small particles interlock with each other to
form unstable lumps (Figure 12). Such agglutinations usually break
up into individual particles during pressing.

Electrolysis

The electrolysis of aqueous solutions is practicable for
obtaining powders of electropositive metals such as copper.
Electrolysis is the most widely used method for obtained copper
powder. Much less practicable and widely used is the electrolysis
of aqueous solutions for electronegative metals such as iron, in-
asmuch as difficulties are found to increase in such instances
with repect to sedimentation and drying of the metal.

In electrolysis of copper, the sediment is generally
desposited on the cathods directly in powdered form. For iron
it is more practicable to have a deposit of a brittle precipitation
in a more or less compact form, which is later subjected to mecha-
nical comminution.

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The conditions most favorable for the formation on the cathode of a powdery precipitate which is easily removed and dispersed consist of a weak concentration of ions of the metal in the original solution, with not too high a temperature, and a strong, steady current. By regulating these factors and the circulation of the electrolyte, an increase of which decreases the dispersability of the powder, one can obtain a product according to the desired characteristics (21).

After being removed from the cathode, a powder is washed, filtered, and dried according to any of the following methods.

(1) Drying in a vacuum with a 50-100 millimeter residual pressure.

(2) Drying with superheated steam.

(3) Drying in a reducing atmosphere (hydrogen, generator gas, illuminating gas).

(4) Drying in boxes covered with coal.

The particles of powders obtained through the electrolysis of aqueous solutions have a chracteristic dendrite structure (Figure 13).

The advantages of electrolysis include: (1) high purity of powders thus obtained; (2) good compressibility (sometimes only after annealing) and sintering capacity of such powders; (3) ease of attaining standardized production; (4) equal adaptibility for work on a large or small scale; (5) possibility of using

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impure raw materials; (6) possibility of separating valuable components from anode sediments (silver and gold for copper and metals of the platinum group for iron).

However, with respect to electronegative metals, these features are often submerged by the diffulties involved in precipitation and drying. The expenditure of electricity for obtaining copper powders is about 2-3 kilowatt hours per kilogram (depending on the dispersion).

The electrolysis of molten media is used for producing powders of certain rare metals (Ta, Nb, Tl, Th, Zr, V, U) which are difficult to obtain by any other way.

B. THE STUDY OF METAL POWDERS

Structural Elements of Powder

Metal powder is composed of small bodies, so-called particles varying in size from 0.1 micron to several millimeters. (The expression "particle" cannot be considered satisfactory inasmuch as a particle is a solid body and not a part. A better expression would have been "small body" or "corpuscle". However, the author uses in this book the more widely used term "particle".) The size of a particle varies for most industrial powders from several microns to 0.5 millimeters.

Sometimes particles combine through interlocking into rather large agglutinations, such as are found in fine powders obtained through reduction (Figure 12).

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Particles in their turn are sometimes composed of smaller subdivisions, microscopic or submicroscopic. Thus, the particles of metal that have been physically pulverized (Figure 14) may be broken down into crystallites (granules), while particles of powders obtained by the splitting of carbonyls (92) or by electrolysis are subdivided into submicroscopic structural elements which are in size on the order of 0.01 microns.

Particles may also have internal cracks, internal capillaries and pores, while admixtures — both surface and intraparticle.

Shapes of particles are quite varied. They are determined by the means of producing the powder; at the same time the size desired for particles may be controlled by the method of fabrication. Particles may be classified according to shape into three principal groups:

(a) fibrous or needlelike particles whose length considerably exceeds other measurements (Figure 15a). Needlelike structure is possessed by thin cast iron shavings (Figure 16);

(b) flat particles (disks, leaves, tablet shapes), the length and width of which is many times greater than the thickness (Figure 15b). Such shapes are possessed by metal paint particles;

(c) equiatial particles with approximately the same size in regard to the different dimensions (Figure 15c).

Figure 13. Electrolytic Brass Powder magnified X 500 (Bal'shin).

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Figure 14. Pulverized Cast Iron Magnified X 500 (Bal'shin).

a   b   c

Figure 15. Structure of Particles: a - Fibrous (Needlelike); b - Flat;
c - Particles with Equal Axes.

Figure 16. Semisteel Shaving. X 20 (Bal'shin and Nemets).

Many variations of these basic groups exist as well as
transitory forms between them. For example, particles having
equal axes may be classified into spherical (Figure 17) and
multigranular (Figure 18). Dendritic structures obtained by
electrolysis (Figure 13) approximate in certain cases needle-
like shapes, while others, equiaxial and flat shapes.

Particles have numerous surface protrusions and pits, as
well as capillaries and at times intra-particle pores — micro-
coscopic and submicroscopic. One may differentiate between
smoother and rougher particles.

a

b

Figure 17. Carbonyl Iron:
a - non-corroded; b - corroded. X 500 (185)

Figure 18. Mos Copper Obtained by the Action of Filings on
Copper Sulphate.

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Figure 19. Diagram of the Structure of a Particle:
1 — metal core; 2 — oxidized outer layer with un-
even relief containing moisture and gases.

The total surface area of particles of powder is very great.
It increases in inverse proportion to the diameter of the particles.
The surface volume of particles is generally taken in relation
either to 1 gram or 1 cubic centimeter of material; this is known
as the so-called specific surface. As a result of the rough
surface of particles of powders the surface as determined by the
adsorption of coloring materials is greater by many hundreds
and thousands of times than the geometric surface computed on
the basis of microscopic measurements (70). The specific surface
of such powders sometimes is measured in tens and hundreds of
square meters per gram.

Particles of powder are as it were a universe in miniature
— Figure 19. Similar to the planets, such as the Earth, parti-
cles have a metal core (oxides are to be found in the central
zone of reduced powders), an outer oxidized layer (the volume of
which is 10 percent and more of the total size of the particles)
similar to the lithosphere, and its own kind of hydrosphere and
atmosphere — adsorbed gases and liquids. The Earth's surface
is covered with countless fragments of rock, sand, stones, etc.
Particles are also studded with fragments of brittle oxides.
The protrusions and hollows on the surfaces of particles corres-
pond to mountains, mounds and depressions of ground relief.
The hardness of surface oxides varying in degree of moisture may
also be modified in the same way as, for example, clay.

Dry oxides may be hard and brittle like stones and dry clay, moist ones -- soft and plastic like dough or soft clay.

Powders, as has already been pointed out (page 16 of original text), are characterized by incomplete mutual contact of particles forming, as it were, a skeleton of the powder and separated by interparticle pores.

Pores with respect to unpressed metal powders take up more than 50 percent, usually 70-85 percent, of the total volume. In certain instances pores take up to 98 percent of the volume of the powder. Figure 19 visually demonstrates the large amount of space taken up by pores and how little space there is for contact among particles (it should of course be taken into consideration that the microphotograph shows a cross-sectional view and that the number of places of contact in space is considerably greater).

In terms of absolute size pores are classified as being macroscopic, microscopic, and submicroscopic. The size of interparticle pores increases with the size of the particles and decreases with the density of their packing. Together with interparticle pores, the size of which is on the order of the size of individual particles of a powder, there are to be encountered large spaces which exceed many times the size of individual particles. Experiments (174) carried out with lead shot showed the formation of large spaces due to a kind of "arch effect" formed by overlapping among particles (Figure 20). Indirect evidence of the size of such pores is given by their permeability to gases and liquids, the greater the permeability the bigger the pores.

On the basis of experiments carried out by a number of investigators one can make the conclusion that permeability (the amount of liquid or gas that can pass under specific conditions during a unit) of time through a body of powder having a fixed surface and thickness) is proportional to the specific surface of particles and consequently to the square of the diameter of particles (or the square of the diameter of pores).

Maximum permeability is observed for particles of uniform size. In a collection of particles of varying size, the smaller particles fit into the spaces between the larger ones and decrease the size of pores and the degree of permeability.

The structure of particles also has an effect on permeability. Under different circumstances, the greatest penetrability is to be found in powders with smooth spherical particles possessing a minimum specific surface and exerting the greatest resistance to the flow of a liquid or gas.

Not ong ago there was published a very interesting article by V. V. Tovarov (Zavodskaya laboratoriya, Number 1, 1948) regarding the penetrability of powder bodies. V. V. Tovarov utilized measurements of penetrability in successfully determining the size of specific surface of powder materials.

Pores are divided into open (communicating, capillary) and closed (isolated) on the basis of their accessibility to liquids which do not react with the powder (such estimates are ordinarily made with oil). (It would have been more exact to divide pores not into opened and closed, but into accessible and non-accessible

with regard to a given liquid in the conditions of carrying out
the experiment. Thus, Tamman's experiments showed that seemingly
isolated pores in solid metals could be penetrated by liquids
under great pressure.

Figure 18 shows visually that all interparticle pores
are intercommunicable for unpressed metal powders. Inraparticle
pores may also be either open or isolated.

Powders as Conglomerates of Particles (Free-Flowing Body)

Powders, considered as the aggregate of a very large number
of particles, the dimensions of which are very small in comparison
with the volume of the entire conglomerate mass, belong to the
class of so-called free-flowing bodies. Thus, the number of par-
ticles in 1 cubic centimeter of industrial powders, such as tungsten,
molybdenum, and tungsten carbide, reaches several million.

Free-flowing bodies considerably differ from regular compact
bodies of metal whih are also conglomerates, not of particles but
of crystallites (granules). The principal points of difference
between a free-flowing body and a hard solid body may be reduced
to the following.

(1) Free-flowing bodies are to be distinguished by incom-
plete contact (quite frequently less than a millionth part of the
particles' surface), solid ones by practically complete contact
between the structural elements.

(2) Contact between the granules of solid metals is prac-
tically constant and hardly changes in deformations caused by

weights which do not fracture the body. Contact between the particles of free-flowing bodies is not constant and changes practically in proportion to the weight.

(3) The structural elements of solid metals are deformed both because of the deformation of the entire body and of neighboring crystallites. Moreover, a change in the contours of each individual granule produces a deformation both of the entire body and of the surfaces of neighboring granules. In contradistinction to this, particles of free-flowing bodies possess "individual adaptation". In compressing a porous free-flowing body, the deformation of each individual particle results to only a small degree in the deformation of the total size of the body and of neighboring particles.

(4) The interlocking of the particles of a free-flowing body is insignificant. For this reason the stability of a free-flowing body is determined principally by mechanical interlocking of particles at their places of contact and is considerably less stable than that of solid bodies. One can add two important conclusions to what has been said on the stability of free-flowing bodies. Mechanical interlocking of particles increases almost in proportion to the surface of mutual contact and this surface varies in its turn approximately in proportion of the pressure. For this reason the stability of a free-flowing body increases almost linearly with the pressure being exerted on the body. Secondly, the stability of free-flowing bodies is many times greater (probably tens and hundreds) under compression than their stability in stretching, inasmuch as the contact between the

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particles increases in the first instance and decreases in the second.

(There is quite widespread the false view that free-flowing bodies are not susceptible to tension (98). In actual fact free-flowing bodies are susceptible to tension to the order of 1 percent or less from existing pressure (i. e., the weight of unpressed bodies). In this way such bodies can disintegrate because of the action of tensions created by loads less than their weight.)

One may note a certain similarity between liquids and free-flowing bodies. In the same way as liquids, free-flowing bodies due to the action of their own weight assume the form of the vessel which contains them. However, it should be emphasized that there is, as will be pointed out below, much greater differences than similarities between free-flowing and liquid bodies.

The "fluidity" (more accurately "friability") of powders is considerably less than that of liquids. Powders do not so completely nor so quickly fill up all possible convolutions of a complicated form. When pressing powders one cannot obtain parts of the same complex form as in casting under pressure. Lesser fluidity is explained by the considerable inner friction existing in free-flowing bodies. In contradistinction to liquids, powders freely poured out do not disperse in random fashion but form a cone-shaped pile. The angle of the pile formed with respect to a plane, the so-called angle of repose, is determined by the friction of the particles. The pressure within a liquid is

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transmitted equally in all directions in accordance with Pascal's
law. In contradistinction to this, specific pressure in free-
flowing bodies in directions perpendicularto the line of its
application has a magnitude of about 20-30 percent of the applied
specific pressure. The pressure is not distributed evenly even
within individual particles of the powder because it is localized
primarily at the contact points of the particles. In contradis-
tinction to liquids, the particles of a free-flowing body do not
occupy the full volume of a vessel in which they are contained
but only a small part (15-40 percent). Deformations in the volume
of a liquid in a vessel are elastic and reversible. The volu-
metric deformation of free-flowing bodies is to a considerable
extent irreversible. Liquids are isotropic. In contrast to them,
the particles of a free-flowing body are usually oriented (the
largest cross-section being perpendicular to the force of the
weight). For this reason the properties of free-flowing bodies
(such as porosity, permeability to gas, electricalconductivity) are
often not the same for different directions.

Properties of and Technical Control over Powder

Those properties of powder which are of technical and
scientific interest consist of the following: composition
(contents of an admixture), magnitude, form and structure of
particles, magnitude of specific surface, porosity and volumetric
characteristics, fluidity, strength, hardness, permeability with
respect to liquids and gases, electrical conductivity, compressi-
bility, and sintering capacity. At the present time we can only

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get an indirect understainding by means of volumetric and compre-
ssion characteristics. Permeability and electrical conductivity
has up to now not been studied for unpressed metal powders.
Microhardness of powders may be determined by the instruments
designed by Khrushchov and Berkovich. For unheaped particles
it is approximately equally in Brinell hardness to the metal from
which the powder has been fabricated. One can also determine the
hardness of a powder indirectly according to the compression
diagram (see Chapter IV). Pressing and baking of powders are
considered in Chapters IV and V. The determination of the
size of specific surface of powders is done by measuring the
adsorption of dyes and other agents, the speed with which they
dissolve in acids, alkalis, etc. However, such calculations are
carried out only in scientific research laboratories and are not
used in technical control. For this reason we do not stop to
consider them in the present book and limit ourselves to refer-
ences to specialized literature (31, 99, 100, 165, 167, 190, 194).

Technical control of metalloceramic manufactures usually
involves the investigation of the composition of powders, the
size, shape, and structure of particles and their distribution as
to magnitude, volumetric characteristics (porosity), and
flowing qualities.

(a) Contents of Admixtures

The contents of admixtures and methods of analysis are
determined by technical conditions, which are quite distinct for
different powders. Usually the permissible contents of admixtures

in powders are determined by the permissible contents of finished products with the exception of acids which are reduced in baking. For this reason most technical conditions permit a relatively high content of oxygen in powder amounting to from 0.2 to 1.5 percent, which is equivalent to an acid content amounting to 1-10 percent. A larger content of oxygen is not recommended inasmuch as it decreases compression and strength of briquettes, the physical characteristics of baked products, and their standards. We wish to point out that oxides as contained in certain powders are not always reduced under existing methods of baking. For example, a large part of admixtures of SiO_2 and MnO (up to 1 percent) found in iron powders restored from slag is not reduced by baking. In the same way the oxidized films of aluminum particles are not reduced with the ordinary methods of baking.

In order to reduce oxides of aluminum it is necessary to add hydrides such as TiH_2 to the mixture for they are a source of atom (atomarnyy) hydrogen (194). The presence of oxygen and sometimes other admixtures increases with the dispersion of powder (growth of specific surface).

(b) Size and Structure of Particles

The size and structure of particles is generally determined with the aid of a microscope. Moreover, it is often necessary to obtain cross-sectional views of particles. For this purpose a small amount of the powder is poured into a crucible and covered over with a bakelite varnish (other transparent plastics may be used). Then the crucible is placed in a thermostat and

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gradually heated from a temperature of 60 degrees to one of 140 degrees over a period of 12-48 hours for the purpose of hardening the bakelite, after which the sample is removed from the cooled crucible and burnished and polished in the usual way. In quantitative measurements of such cross-sections it should be kept in mind that the plane of the cross-section is not always at right angles to the particles with respect to the main diameter and that the observed average diameter is smaller than the main one.

In spherically shaped particles it is according to Agte:

$$d = \frac{\pi}{4} D = 0.79D.$$

$$(1)$$

where D is the main diameter and d the average observed diameter for the cross-sections of particles.

In examining powders poured on a microscope slide with the aid of passing light one is able to directly establish the principal diameter of particles.

For certain fine powders, such as tungsten, cobalt, iron, etc., obtained through reduction, microscopic measurement of dispersion is distorted as a result of agglutination of particles. In such cases one may resort to rubbing down the powders with turpentine by means of a glass rod. One may also determine the size of such powders using cross-sections of criquettes which have been compressed to a specific porosity because of the fact that the agglutinations are broken up into individual particles upon being pressed.

In order to determine the size of particles of a powder and their distribution as to size, screen analysis is usually resorted to, i.e., sifting a powder through a number of screens of different size. Typical screen analyses of powders are given in Tables 3 and 4. The size of a screen is measured either in terms of the size of the holes or the number of mesh, i.e., the number of holes per linear inch (dyuym).

(c) Volumetric Chracteristic of Powders

The volumetric characteristic of porous bodies and powders may be expressed in terms of one of the following magnitudes.

(1) The volumetric weight γ is the weight of a unit of volume of bodies. Expressed in grams per cubic centimeter.

For powders there is the poured weight, which is the weight of a unit of volume of freely poured powder, and shaken-down weight which is the weight of a unit of volume of shaken-down powder.

(2) Volume of weight ω is the volume of a unit of weight of a porous body. Expressed in cubic centimeters per gram:

$$\omega = \frac{1}{\gamma}$$

(2)

(3) Relative density θ is the relation of the density of a powder to the density of the powder material:

$$\theta = \frac{\gamma}{d}$$

(3)

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where d is the density of the powder material. Relative density is characterized by a part of space occupied by the powder material (the skeleton) and is expressed in an abstract figure -- a proper fraction or in percent ($\theta < 1$ or $\theta < 100$ percent).

(4) Relative volume β is an abstract figure showing how many times the volume of a free-flowing body is greater than the volume of the material of the powder. Expressed as an improper fraction or in percent ($\beta > 1$ or $\beta > 100$ percent):

$$\beta = \frac{1}{\theta} \tag{4}$$

(5) Porosity P characterizes that part of the volume which is taken up by pores and is usually expressed in percent ($P \angle 100$ percent):

$$P = 1 - \theta$$

or

$$P = 100 \text{ percent} - \theta \tag{5}$$

(6) The coefficient of porosity ε is an abstract figure showing the relation of the volume of pores to the volume of hard material in a free-flowing body. Expressed in an abstract figure or in percent, it may take any value from 0 to infinity:

$$\varepsilon = \beta - 1$$

or

$$\varepsilon = \beta - 100 \text{ percent} \tag{6}$$

Poured weight, the weight of a unit of freely poured powder,

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is determined by means of a volumeter (Figure 21). A volumeter consists of a funnel with a screen and a casing with several inclined glasses along which the powder in being poured falls into a crucible of a known volume and weight. Surplus of powder is removed from the crucible with a steel rule, after which it is weighed on an analytical balance. The poured weight of the powder is determined by means of dividing the weight of the powder in grams by the volume of the crucible in cubic centimeters.

Poured weight can also be determined with instruments used for measuring the flow of powder (Figure 22).

Knowledge of the volumetic characteristic of powders is of the utmost importance for metalloceramic production.

The volumetric characteristic determines the compression factor of powder in pressing. For example, if the relative density of an unpressed powder is 25 percent and of pressed powder 75 percent, it is obvious that the powder is compressed $\frac{75}{25}$ or 3 times and the height of the press mold must be three times greater than the computed height of the pressing. A knowledge of the volumetric characteristic is very important for pressing with automatic loading.

Finally the volumetric characteristic determines the "Structural" strength of a powder (8). One may look upon a free-flowing body as a structure under a definite load (that of its own weight). The greater the structural strength of a powder the less can it be deformed by weight and the lighter is its poured weight (in the same way that the greater the strength of

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a material the lighter can be the part manufactured for operating
under a given load). Let us note that for powders of identical
composition a decrease in poured weight of two times corresponds
to an increase in structural strength of several tens of times.

The density of packing of powders depends on very many
factors. These factors usually modify structural strength, while
strength determines the volumetric characteristic of a free-
flowing body.

Figure 21. Volumeter.

Figure 22. Instrument for Measuring Flow (156):
1 - stainless steel funnel; 2 - bracket; 3 - crucible.

Let us enumerate the principal factors.

(1) Size of particles. The structural strength of a pow-
der is due for the most part to the interlocking of the rough
surface layers of the particles. Small-grained powders generally
have a greater relative roughness than large-grained. For this
reason in the majority of cases (but not all cases), structural
strength and poured weight decrease with an increase in the size
of powder particles.

(2) Shape of particles. A fibrous and dendritic shape
assures the greatest amount of interlocing and interlocking for
particles. For this reason these powders are the most durable
and light. On the other hand, powders with particles that have
equal axes and are especially round are the heaviest. The greater

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the roughness of the surface the more stable and light is the powder.

(3) Size distribution of particles. Where a mixture contains both small and large particles, the former may be located between the latter, thereby making the packing more solid and increasing the poured weight.

(4) Intraparticle porosity. Internal pores increase the size of particles without decreasing their surface strength. For this reason particles with intraparticle porosity have a lighter poured weight than powders with compact particles.

(5) Surface oxides. Oxides are more brittle than the basic metal. For this reason the formation of oxides always results in a decrease of strength and in an increase of poured weight (in spite of a decrease in the specific weight of the material).

(6) Processing of powders. Processing in ball mills increases for the majority of cases the poured weight of powders, inasmuch as it brings with it a decrease in the surface roughness of particles, destruction of the surface layer and a decrease in its strength.

The volumetric characteristic is given for a number of industrial powders in Table 4.

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Table 4.

RELATIVE DENSITY OF SOME INDUSTRIAL POWDERS

Powder	Relative Density in Percent	
	Poured	Shaken Down
Electrolytic copper	12-35	20-45
Electrolytic iron	20-36	30-50
Reduced iron	10-25	20-40
Reduced tungsten	10-25	20-40
Carbonyl iron	35-40	45-50
Granulated tin, copper, lead	30-50	40-65
Vorticity processed iron	25-35	30-40

Together with the volume there is a change in the size and all other characteristics of a porous body. It is frequently found necessary to make use of so-called "reduced" sizes, i. e., sizes corresponding to the compact body of the same mass as that possessed by a porous body.

We shall give several examples. The reduced volume of a freeflowing body V_c is the volume of the compact material (skeleton) of a powder when V is the volume of the porous body

$$V_c = V\theta$$

(7)

and   is the relative density.

The reduced height h_c of a pressing is the height of the

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briquet with the same cross-section compressed into a compact state

$$h_c = h\theta$$

where h is the height of the porous body and θ its relative density.

The reduced specific work of pressing is the work of compressing a quantity of powder corresponding to a cubic centimeter of a compact material.

(d) Fluidity of Powders

The fluidity of powders is measured by taking the quantity of powder in grams which would flow during the course of one minute under fixed conditions through a narrow opening of a fixed diameter. The knowledge of such a quantity is of essential importance for automatic pressing.

Figure 22 shows a model of an instrument for determining fluidity which can also be utilized for measuring poured weight. The powder flow through a conical funnel made of stainless steel whose cone has an angle of taper of 60 degrees. The diameter of the narrow part of the funnel is 2.5 millimeters. The length of the narrow part is 3 millimeters. The weight of the powder that passes through during a unit of time is recorded (156).

The fluidity decreases with an increase in the interlocking and friction among particles. For this reason it is considerably less for fine powders with a large value for the specific surface

and a large ratio of surface to the weight of a single particle.
In the same way the fluidity decreases with an increase in the
roughness of particles and a decrease in the poured weight of
the powder.

The Effect of the Properties of a Powder on the Properties
of the Finished Product

The effect of the properties of the original powder on
pressing, baking and the properties of semifinished and finished
products are considered in greater detail in Chapters IV, V, and VIII.
With identical conditions of manufacturing, the properties of
finished products generally depend to a considerable extent on
the properties of the original powders. For example, there are
obtained from powders that have greater permeability finished
products with greater permeability. For this reason filters
(Chapter XIV) are made from powders with relatively big spherical
particles of identical size. The more "durable" powders of
small poured weight usually give (other factors being equal)
more durable semifinished and finished products. At the same time
light powders possess a number of defects, such as the necessity
of using press molds that are very tall and which require greater
pressure for pressing, which factors, in turn, are conducive
to increased wear of the press mold, slow rate of flow, etc.
At present powders are preferred in the majority of cases with
a relative density of 25-35 percent for poured masses. In
baking small-grained powders with a large specific surface, there
is a more significant increase of contact among particles of a metal
powder due to the action of increase mobility of surface atoms

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(Chapter V). For this fine dispersible powders result in products under identical conditions of manufacture with the best properties. In the same way it is frequently better to use a mixture of finer powders for obtaining uniform alloys. At the same time the use of fine powders involves a number of difficulties — easy oxidation, a large admixture content, poor fluidity, increase of compacting pressure, poor permeability, damage and buckling in settling, difficulty of complete reduction during baking because of small gas permeability, etc. But its most important defect is to be found in the high cost of fine powders. It should be noted that the properties of products from fine powders are better only under identical conditions of manufacturing products. For this reason there has developed recently a completely justifiable tendency to base operations on economic factors and thus transfer over to coarser powders. Of course there are special cases where it is necessary to ignore this rule. Thus, it is not possible to use coarse powders for pressing small thin-walled parts. The cores of induction coils (Chapter XVI) are often prepared from fine powders of carbonyl iron in spite of the high cost.

Chapter III

PREPARATION AND COMPOSITION OF POWDER MIXTURES

Preparatory operations have for their purpose the obtaining of powder mixtures having a definite chemical composition and a definite degree of dispersion and other physical properties. These operations may be broken down into mixing and preliminary processing of powders.

In grading the original powders composed of different sized particles, they are subdivided into two or more groups of specific size.

On the other hand, when mixing two or more original powders having a different chemical composition or disperion, there is created a powder mixture having the required composition and physial characteristics.

Preliminary processing, whether thermal or mechanical, has for its purpose the modification of the physical characteristics of powders, such as the degree of dispersion, compressibility, etc. Sometimes the preliminary treatment may be combined into a single operation with mixing or grading. Thus, when mixing powders in a ball mill, one can simultaneously do mixing, pulverization, toughening and increasing the poured weight of the original powders.

CLASSIFICATION OF POWDERS (GRADING)

In separating metal powders into categories according to

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particle size, apparatus of the type ordinarily used in the chemical industry or ore dressing is used.

In order to separate the relatively coarse groups of particles with a diameter exceeding 50 microns, powders are sifted through wire or silk sieves. Metal wire sieves are generally made from brass, copper, or bronze.

Various type sieves are used in sifting. Preference should be given in the majority of cases to enclosed models which prevent the diffusion of powders throughout the building. Figure 23 shows an enclosed screen designed by TsNIITMASH (8). The bucket together with the screen (sieve) is caused to oscillate by an electrical motor through a texrope transmission and a system of controls. The number of oscillations of the bucket is 156 per minute while the range of oscillations stays within the limits of 20 to 120 millimeters. The powder to be sifted is poured into the bunker and then falls through a pulsating feeder onto the screen. Having gone through the screen, the powder passes through a bunker under the screen and falls into a wagon container. The residue remaining on the screen is removed by hand. The bucket, bunker, and wagon are enclosed in a case with two pairs of doors, the upper for observation, removal of residues, installation, and repairs, the lower for taking out the wagon. To prevent the powder from filtering into the workroom, the doors have hermetic rubber and felt lining. With respect to this consideration provision has been made for attaching the case to a ventilator.

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Figure 23. ToNIITMASH Sieve.

Figure 24. Open Sieve.

Figure 25. Mechanical Sieve (186).

Figure 24 pictures an easily portable open mechanical sieve
(148), while Figure 25 shows a handy enclosed sieve (186). The
great ease of portability, inexpensiveness, and productivity serve
to distinguish electromagnetic sieves, which do not require an
electric motor or wires to cause them to operate and which are
fed directly from the illumination network. However, the sieve
cloth is clogged very quickly by the powder and goes out of
commission.

For sifting powder mixtures which containing sticky or lubri-
cating agents, it is sometimes found necessary to rub the mixture
through the sieve either by hand or mechanically. Classification
of powders into categories by sifting through a sieve is possible
in practice only for sizes up to 250-300 mesh. For this reason
it is necessary to resort to air (separation) classification for
powder particles smaller than 40-50 microns. Air classifiers
(separators) are sometimes included in the equipment for manufac-
turing powders (Figures 5 and 6).

MIXING OF POWDERS

The mixing of powders requires the expenditure of more or
less considerable work for overcoming friction and interlocking

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among the particles being mixed. Existent methods of mixing may be broken down into the following basic types.

(a) Mixing in drums with excentric axes of rotation. The overcoming of friction among the particles and their mixing is achieved by means of shaking off of the powder as it is being rotated around an excentric axis. Figure 26 shows a mixing drum designed by TsNIITMASH. The drum makes 30-40 rotations per minute. The capacity of the drum, depending upon the scale of production, varies from 100 to 500 liters. The recommended coefficient in filling with powder mixture is 1/3. The time required for mixing takes about 1 hour.

(b) Mixing in ball mills with steel balls. In mixing the particles friction is overcome by the colliding action of the balls. The greater the pulverizing result to be achieved in ball mills, the greater must be the total weight of balls with respect to the total weight of the powder mixture.

(c) Wet mixing in ball mills. In this case friction among the particles being mixed is weakened by the action of the liquid (water, alcohol, benzine) and results in a more thorough mixing than with the dry method.

Figure 26. Mixing Drum.

Figure 27. Vibratory Mill.

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(d) Vibratory mixing, dry or wet. The overcoming of friction
among the particles being mixed is aided by having the balls pul-
verizing the mixture also vibrate. Vibratry mills (Figure 27)
have come to be used in the hard alloy industry (142). Their adop-
tion has made it possible to shorten the time of pulverization
by six times.

Dry mixing in drums is found practicable for use in the
following cases:

(a) for powders of soft metals which are greatly deformed
when processed in ball mills;

(b) for metallographite mixtures, inasmuch as graphite
particles when processed in ball mills may often completely
coat the metal particles, which reduces the strength of products;

(c) when it is necessary to limit reciprocal reaction
among the components of a mixture;

(d) in those cases where especially thorough mixing is not
required.

On the other hand, where it is necessary to increase the
reaction among the components (as in the manufacture of hard
alloys) and where particles must be pulverized and carefully mixed),
preference should be given to mixing in ball or vibratory mills.
When it is especially necessary to obtain a carefully mixed
mixture (such as in fabricating tungsten-titanium hard alloys),
recourse is had to the very prolonged wet mixing in ball mills
sometimes taking up to 5 days.

For certain cases there is practiced the introduction into

the powder mixture of components in the form of oxides or their
solutions (usually for ductile metals in cases where they comprise
a small percentage of the mixture).

Sometimes it is necessary to mix metal powders with organic
elements (such as rubber, stearic acid, zinc ether or stearic
acid, glycerine, etc.). Usually in such cases the mixture
is dissolved in a solution of the required component contained in
a volatile organic solvent (benzine, alcohol). After the solvent
has volatilized, the particles of the powder are covered with a
more or less thick film of the introduced element.

PRELIMINARY PROCESSING OF POWDERS

In a number of instance powders are subjected to a
special preliminary mechanical or thermal processing, or their
combination, for the desired change of their properties.
Such processing may be done together with mixing or sifting.

We have already spoken above about the processing of
powders in ball mills during mixing for the purpose of pulveri-
zing then and increasing their poured weight.

A preliminary heat treatment of powders is often practiced
for the purpose of increasing their plasticity and compressibi-
lity (through reducing oxides and removing cold hardening).
Sometimes heating is used for obtaining homogeneous hard solutions
— homogenization of a mixture (annealing of brass-zinc
mixtures, annealing of carbides of tungsten and titanium, etc.).

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Preliminary thermal treatments are carried out in a protective or reducing medium at a temperature of 60-100 degrees below the baking temperature (it very rarely happens that it exceeds the baking temperature). Such annealing quite frequently is done in baking ovens.

Chapter IV

PRESSING

Pressing of powders has for its purpose the molding of semifinished products having the dimensions and form necessary for obtaining finished products with allowance being made for deformations caused by later operations (baking, calibration, etc.). The strength of Criquettes must be adequate for them to withstand handling without breaking down prior to sintering (transfer and packing).

Pressing more than any other operation in metalloceramic technology, including baking, limits the possibilities of powder metallurgy. First of all, the f rm and dimensions of products are entirely determined by the possibilities of pressing. The possibility of using one or another method for the fabrication of powders from a given metal also depends on the pressing characteristics of the powders being produced. Finally, the possibility of obtaining metals and alloys of a given composition also depends to a certain extent on the pressing operation. It was thought for a long time that it was impossible in principle to obtain metalloceramic aluminum because its oxides could not be reduced during baking. However, the work of a number of investigators showed that it is possible to prepare metalloceramic aluminum and that earlier experiments had given negative results only because of the fact that at that time it was not known how to obtain satisfactory briquettes of aluminum.

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A. TECHNOLOGY AND EQUIPMENT

Pressing of powders is done in hydraulic or mechanical presses using tempered steel press holds.

Pressing is composed of the following operations:

(a) measuring off and pouring the powder mixture into the press mold,

(b) pressing,

(c) removing of the semifinished product from the press mold.

Measuring Off and Pouring

Measuring off of the powder mixture is done either by weighing with automatic-by volume. When measuring off in hand weighing, weighing is done for the most part on a laboratory balance. The handling of portions being weighed or poured into a press mold is generally done with the help of small tin cups. Sometimes automatic scales (Figure 28) are used for weighing portions (186). The accuracy of weighing on such scales (186) for small briquettes at a rate of 4-5 portions per minute is about plus or minus 1 percent. To lighten the task of pouring into press molds there may be used tin funnels placed into openings in the receiver of the press mold. Sometimes the actual receiver of the press mold has arrangements in the form of conical or funnel-shaped openings at the loading end. Attention should be paid to evenness of pouring and to the levelness of the surface of the powder in the press mold. This is achieved in

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various ways — by shaking the press mold by hand, (such as by knocking with a wooden malet), by mechanical vibration, by using press molds the volume of whose load has been exactly ascertained with respect to a given portion of powder (this method is used especially in automatic pressing), and, finally, by using special leveling devices.

Figure 28. Automatic Scale.

Figure 29. Leveling Out a Poured Mixture.

Figure 29 shows a poured mixture being leveled in the pressing of a disk as described by Gardin (32). The press mold is set up on a rotating table. The poured mixture is leveled out by a stationary leveler while the press mold is being rotated.

Press Molds

Present-day press molds have a considerable number of parts. However, the principal parts are three — the mold or matrix, which shapes the side exterior of the briquette; the die (plunger), a movable part which shapes the upper surface and compresses the powder; the stand or holder, which shapes the bottom surface of the compact and prevents the powder from falling out of the press mold (Figure 30). Besides these three fundamental parts there are various auxiliary parts which make it possible to remove the press mold, assure exactness of the size of the briquette dimensions (controlling guides), cause compression to be even from both ends, etc.

a   b

Figure 30. A Cylindrical Press Mold.

a — pressing; b — pressing withdrawal;

1 — mold; 2 — plunger; 3 — base; 4 — stand

for pressing withdrawal; 5 — compact.

Figure 31. A Dismountable Press Mold.

1 — shoe; 2 — bolt; 3 — cheeks;

4 — plunger; 5 — lining; 6 — compact.

Figure 32. A Dismountable Press Mold (194).

Press molds consist of two types classified according to
the way a briquette is removed — by ejection of a product
after pressing (Figures 30, 33, 34, 35, 36, 37) and by removal
of a product by dismantling a press mold after pressing (Figures
31 and 32). In the case of manual press molds, the base is
removed after pressing and the mold is placed on a special
stand (Figure 30b). Then the die is depressed and the product
is thereby ejected. The pressure to secure ejection varies from
5 to 60 percent of the compacting pressure (depending on the
height and cross section of the product and the use of lubri-
cating agents). In press molds mounted on presses the ejection
is done from below by means of a special pushrod which replaces
the base. This pushrod may serve at the same time as a lower
plunger (Figure 33). In ejection the product expands somewhat
through elastic after effect usually up to 0.3 percent with
respect to the diameter and 0.5 percent with respect to height.

- 4 -

a   b

Figure 30. A Cylindrical Press Mold.

a - pressing; b - pressing withdrawal;

1 - mold; 2 - plunger; 3 - base; 4 - stand

for pressing withdrawal; 5 - compact.

Figure 31. A Dismountable Press Mold.

1 - shoe; 2 - bolt; 3 - cheeks;

4 - plunger; 5 - lining; 6 - compact.

Figure 32. A Dismountable Press Mold (194).

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the way a briquette is removed — by ejection of a product
after pressing (Figures 30, 33, 34, 35, 36, 37) and by removal
of a product by dismantling a press mold after pressing (Figures
31 and 32). In the case of manual press molds, the base is
removed after pressing and the mold is placed on a special
stand (Figure 30b). Then the die is depressed and the product
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height and cross section of the product and the use of lubri-
cating agents). In press molds mounted on presses the ejection
is done from below by means of a special pushrod which replaces
the base. This pushrod may serve at the same time as a lower
plunger (Figure 33). In ejection the product expands somewhat
through elastic after effect usually up to 0.3 percent with
respect to the diameter and 0.5 percent with respect to height.

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Therefore, in order to avoid laminated cracks it is necessary to provide for gradual expansion of the ejection opening (with a taper of 0.5-1 percent in the direction of the axis of pressing). This measure was first carried out in the metalloceramics laboratories of TsNIITMASH (8) in 1937. Sometimes (186) a 10 minute angle of taper is recommended. Dismountable press molds are considerably less useful. For this reason they are used either in pressing briquettes of small tensile strength (tungsten and hard alloys) or in compacts of complex shape. For pressing, dismountable press molds are placed in special shoes (Figure 31) and secured therein by bolts or they are enclosed in a special casing. In the latter case the design of the inner parts makes for easier dismantling. Simultaneous pressing of several parts can take place in multichamber dismountable press molds. At the present time dismountable press molds are going out of use because when using them for pressing it is difficult to avoid the formation of cracks (186).

Figure 33. Press Mold for Bearings (194).

1 - upper plunger; 2 - mold; 3 - core;

4 - lower plunger; 5 - press table;

6 - loading sleeve; 7 - briquette

Control guides are used to guarantee exact heights for briquettes. A control guide is frequently a collection of rings or plates which are placed on the matrix of the press mold and on which the plunger of the press rests. Thanks to this, the plunger upon attaining a certain level stops in its descent, thereby resulting in the

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briquette having a fixed height. But there are also possible other types of designs for such control guides. Thus, there may serve for a control guide an aggregate of plates which is placed on the bottom plate of the press and which stops the movement of the plunger at a fixed level. Finally, it is also possible to do without any control guide whatsoever by designing the die in such a way that it rests on the upper extremity of the mold upon reaching a specific level.

For briquettes with inside perforations, the shaping of the inside surface is done either by the die, the stand, or a special core. Several types of press mold designs are distinguished form each other by this factor.

Press molds for pressing cylindrical products may be broken down into the following types.

(1) Press molds with one-sided pressing in which the shaping of the internal perforation is done by the die. The left sections of Figures 34 and 35 show this type of press mold. The press mold consists of the mold, die, two rings — an upper and a lower — and a stand for pressing. The upper ring is for the purpose of making it cheaper to produce a die and lengthens the period of its service (when worn out only the ring and not the die is replaced). The same function is served by the lower ring for the stand. The advantage of this type of press mold is to be found in the simplicity of design, the disadvantage— in the larger clearance with respect to height.

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For this reason it is useful to employ such press molds for
pressing sleeves with dimensions that are more than 30 millimeters
with respect to diameter and height.

Figure 34. Press Molds.

Figure 35. Press Molds Shown in Figure 34 in Dismantled Form.

(2) Press molds for one-sided pressing which have a spe-
cial core for making an inside hole require less clearance as
to height (right side of Figures 34 and 35) in comparison with
the preceding ones. Press molds of such a type can be used for
pressing cylinders and thick-walled sleeves with dimenstions as
to diameter and height varying up to 60 millimeters.

(3) Press molds with two movable dies, an upper and lower,
(Figures 35, 36, 37), are employed for pressing products with a
large height or with a large ratio of height to diameter or thick-
ness of walls. Such press molds are designed for use with
presses having either a two-sided pressure, upper and lower, (
Figure 33) which blocks the movement of the lower die until the
upper one has moved to a certain level. When this position
is reached, the lining is removed and compression is exerted
from below because of the movement of the matrix in rela-
tion to the lower die. In other cases the premature depression
of the matrix is prevented by a special spring which matches its
weight (Figure 37). Two-sided press molds are generally designed
for objects whose height ranges up to 150-200 millimeters,
sometimes even more. It should therefore be kept in mind that

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even with two-sided pressing and the use of lubricating agents
the height may not exceed wall thickness by more than 15-17
times. It is recommended that the height te no more than two
times the diameter. In recent times there has been noted a ten-
dency, which should be considered justifiable, to resort to
two-sided pressing even for products with a small height. The
advantages of two-sided pressing lie in even density and good
quality of pressing, its disadvantages — in more complex
servicing, larger dimensions, and cost of the press molds.

Figure 36. A TsNIITMASH Press Mold for Two-Sided Pressing.
1 - mold; 2 - core; 3 - rings; 4 - upper die; 5 - lower
die; 6 - lining; 7 - stand.

Figure 37. Press Mold with Spring for Two-Sided Pressing.

The dimensions of press molds are determined on the basis
of the following considerations. The height of the matrix is
equal to the height of the briquette multiplied by the com-
pression factor plus the dimensions of the upper and lower
ring. The compression factor is equal to the ratio of the volu-
metric weight of the compact to the volumetric weight of the
powder. With respect to most ind s trial powders the compression
factor is about 3 while the height of the matrix is 3-3 1/2
times the height of the compact. The dimensions of the die and
other parts have a corresponding calculated height.

The inner diameter of the matrix is equal to the outer

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diameter of the sleeve with allowance being made for changes
in dimensions during baking (see Chapter V) plus allowance for
compression during calibration. Where there is noted a shrinkage
during baking, the inner diameter should be correspondingly
increased, and where there is an expansion, it should be cor-
respondingly decreased. In this way press molds are made not
only in accordance with the specific dimensions of products
but also in consideration of the specific variety of powder
used. Allowance for calibration usually is equal to 0.25-0.49
millimeters (depending on the diameter of the sleeve).

The space between the die (ring) and the press mold
must be suffcient to allow free escape of air during the packing
of the powder. However, too large a space may allow powder to
set there. Kiefer and Gotop (167) recommend clearances varying
from 0.2 to 0.5 percent of the diameter of the compact. TsNIITMASh
(8) considers it more desirable to have smaller spaces (running
and free setting of second grade of precision). Vul'f (Wolf)
recommendseven smaller spaces (Figure 34).

The diameter of the core forming the internal surface of
the sleeve is equal to the inner diameter of the sleeve with
allowance for change indimensions during baking plus allowance
for the space between the calibrated core of the die and the
inside diameter of the baked sleeve. The space usually is equal
to 0.20-0.30 millimeters. The outer diameter of the mold is
calculated on the basis of the yield point of the material from
which the mold is made and the tensions developed during pressing.
The compression pressure grows with the hardness of the original
powders, the density of pressing, and the relation of the height of

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the briquette to the thickness of the walls, and varies between
1,000 and 6,000 kilgorams per square centimeter. The specific
lateral pressure for one square centimeter of lateral surface of
the briquette usually makes up 25-35 percent of the specific
pressure of the compression. Lateral pressure (8) may be com-
puted with the aid of formula

$$(9)$$

where   is the coefficient characerizing the relation of the
late al pressure to the pressure of compression,

is the relative density of the compact,

is Poisson's coefficient for the metal powder,

is the specific lateral pressure,

is the specific pressure of compres ion for a parti-
cular ar a of the briquette.

Table 5.

THE VALUE OF ε' WITH RESPECT TO THE TYPE OF METAL AND DENSITY OF PRESSING

Metal	ϑ - 100%	ϑ - 90%	ϑ - 80%	ϑ - 70%	ϑ - 60%	ϑ - 50%	ϑ - 40%
Tungsten	0.21	0.19	0.16	0.14	0.12	0.10	0.08
Iron	0.39	0.35	0.31	0.27	0.23	0.19	0.16
Tin	0.49	0.44	0.39	0.34	0.30	0.25	0.20
Copper	0.54	0.49	0.45	0.38	0.32	0.27	0.22
Lead	0.79	0.71	0.63	0.55	0.47	0.40	0.33

In designing press molds the considerations described in Chapter XIII relating to the shape and dimensions of parts should be kept in mind. The low fluidity of powders must also be considered.

<div style="text-align:center">a   b</div>

Figure 38. Pressing of Products of Complex Shape.
1 — with one die; b — with two (167).

For this reason, as Gettsel' points out (153), with respect to a product of unequal dimensions the principle should be observed of having an equal factor of compression for all vertical cross sections along the axis of pressing. Two possibilities exist for fulfilling this principle in practice. In the first case, instead of one die there can be used several independently shifting dies (153, 169). Thus, in a press mold with one die (Figure 38a) the density is greater in the center of the compact than at the edges, while in a press mold with two dies (Figure 38b)

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the density in the center and around the edges is equal. In the
other case pressing is done (Figure 39a) by avoiding the
stamping of the final shape which is acquired in a later pressing
after baking (Figure 39b). In this case equality of the com-
pression factor is achieved not by means of one but of two
pressing operations, prior to and after baking (Chapter VII).

a

b

a

b

Figure 39. Pressing Products of Complex Shape.
a — after pressing; b — after baking and second pressing
(Gettsel'). The figures give the relative density for dif-
ferent parts of the specimens.

Figure 40. Pressing of Notched Parts.

The pressing methods used for complex products with
uneven dimensions as to height (196) are pictured with respect
to a number of details in Figures 40, 41, and 42.

The heights of the powder charges and the briquettes
are shown in these drawings in terms of units by means of
broken horizontal lines. The desirable coefficient of com-
pression for the powder with respect to the cases under consider-
ation is equal to 3.

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Where difference in the height of the products does not exceed 25 percent (notched part in Figure 40), compression may be achieved by one upper die (the lower die is used for ejection). The greatest height given for a part is in Figure 40 and consists of 8 units, while the height under the notch is of 7 units. The height of the poured powder consists of 23 units, which is a compromise with respect to the theoretically required 24 units for the greatest height of the unit (24:8 = 3) and to the 21 units for the height under the notch (21:7 = 3). After pressing, the coefficient of compression for the highest places of the briquette is 23:8 = 2.9 and 23:7 = 3.3 under the notch. In this way the coefficient of compression is close to the ideal value of 3 for the different parts of the briquette, while the density is sufficient for the use for which the product is intended. Further equalization of density may be achieved by calibration.

Figure 41. Pressing of a Flanged Part.

Flanged details may easily be made with two-sided pressing, provided that the size of the flange does not exceed 25 percent of the height. In the flanged detail shown in Figure 41a the height of the entire piece is equal to 4 units, that of the flange to 1. The flange part of the press mold has been designed to receive three units of powder, that of the body 12 units. In compression, the upper plunger is depressed by 2 units, the lower is raised 6 units. The coefficients of compression for the flange 2:(3-2) = 3 and for the entire object

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12:(12-6-2)   3 are identical. The part in Figure 41b differs
from that in Figure 41a only by the greater width of the flange.

In this connection a compound lower die has been provided in
order to avoid breaking the flange during ejection.

Figure 42. Pressing a Detail with a Two-Step Flange.

Figure 43. Press Mold for a Complex Detail.
1 - upper die; 2 - detail of upper die with an independent
spring movement; 3 - briquette; 4 - powder; 5 - lower die
6 - matrix.

Figure 42 shows the pressing of a more complex detail with
a two-step flange. The total height of the detail is 8 units
where the height of the longest diameter is 5 units, of the middle
one 1 unit, and of the smallest 2 units. The height of the entire
charge is 22 units with 15 units above the first flange and 16
above the second. The upper die is depressed 10 units, the
lower raised 4 units. A satisfactory compression is thus secured:
total 22:(22-10-4) = 2. 75, above the first flange 15:(15-10) = 3,
and above the second 16:(16-10) = 2.7.

No other ratio for the dimensions of the flange could have
secured a satisfactory density for the second flange, for it
would have been necessary in pressing the detail to resort to a
compound lower plunger composed of two parts or to first press the
detail for one flange and later obtain the second by machining.

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Figure 43 shows the design of a press mold for a complex detail (186).

The press mold has a compound die with a spring and with independent movements for the composite parts.

The most crucial parts of the press mold (matrix) are made in the USSR of EKh-12 steel with a hardness after hardening of $R_c = 60-64$. Mes'kiy (81) considers the KhVG steel to be more suitable. For unimportant parts there are used the less difficulty available steels (U-7, ShKh-15, St. 3, St. 5, etc.). Certain writers (194) recommend for the use of molds and cores high-speed steel with a hardness of $R_c = 62$ after hardening. There are also recommendations (167) to use inserts composed of metalloceramic hard alloys when making many briquettes of details.

Table 6 presents certain data (187) on materials for press molds in terms of the number of briquettes to be pressed.

The longevity of press molds of average diameter used for pressing iron and copper powders is usually 20,000-50,000 briquettes. After this they may be reground over the entire diameter or, after slight repolishing, nitrided in ammonia gas. Nitriding brings on a certain constricture of the inside diameter, thus making it possible to again press products with previous dimensions.

In a number of cases (187) the die and the inner lining of the mold may be reground after 100-200 thousand pressings of iron

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powder. A press mold may be said to have been completely worn
out only after the millionth pressing.

Table 7 gives data on the longevity of press molds made
from different materials.

In mechanical working (grinding) of a detail press molds
become magnetized. In order to prevent the iron powder from
sticking they have to be demagnetized. Demagnetization is done
in an induction coil through which an alternating current is
passed. The demagnetized parts are placed into the opening
of the coil for a few seconds.

Press molds in being installed have to be centered in order
to avoid the plungers of hydraulic presses or those of mechanical
presses from slanting.

The installation of industrail press molds on presses is
shown in Figures 33 and 44. The devices used for installing
press molds are somewhat different from those employed in in-
stalling stamping machines. Figures 45, 46, and 47 show
suggestions for modifyin the designs of these devices (167).
Figure 45a shows the standard construction of a lower die,
Figure 45b a design which eases installation and dismounting,
being specially adapted to the requirements of powder metallurgy.
Figure 46a shows the usual construction of a coupling for
connecting the lower die with the plunger of the press, while
Figure 46b shows a detachable coupling more suitable for
quick installation. The design of the device for installing the
matrix of a press mold is more suitable in Figure 47b than in

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Figure 47a.

For certain cases certain agents are introduced into the powder mixture in pressing which increase the strength of the briquette or decrease friction and increase flow of powders (solutions of rubber with benzine, paraffin, stearic acid, zinc ether of stearic acid, solution of camphor in alcohol, glycerine, etc.). It is recommended that press molds be cleaned after several pressings.

Figure 44. Installation of a Press Mold for Sleeves.

a   b

Figure 45. Lower Die.

a — design usually found in presses; b — design for presses in the metalloceramic industry; 1 — core; 2 — die; 3 — supporting part of the die; 4 — die holder.

a   b

Figure 46. Couplings Connecting the Lower Die to the Plunger.

a — in ordinary presses; b — in presses for the metalloceramic industry.

a   b

Figure 47. Devices for Matrixes.
a — in ordinary presses;
b — in presses for the metalloceramic industry.

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Table 6.

MATERIALS FOR PRESS MOLDS (187)

[1] Number of Parts Pressed by a Given Press Mold	[2] Pressing Pressure	[3] Material of Press Mold			[4] Processing	[5] Hardness R_c
		[a] No	[b] Name	[c] Chemical Composition		
Small or experimental lots	Low Pressure	1	Kirksayt	Alloy with a zinc base and additions of aluminum and copper.		
		2	Cast iron			
		3	Bronze			
		4	Cold-rolled steel		Cementation [case hardening]	

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[1]	[2]	[3]			[4]	[5]
		[a]	[b]	[c]		
	High Pressure	5	Tool steel	0.9% C; 1-1.5% Mn, 0.25% Si; 0.5% Cr; 0.5% W	Oil hardening at 760-790°, tempering at 190-205°	61-62
From 5 to 50 thousand pieces	Low Pressure	5	Ibid	Ibid	Ibid	Ibid
	High Pressure	6	Nickel-chrome tool steel	0.75% C; 0.6% Mn; 0.25% Si; 1.41.7% Ni; 0.75% Cr	Oil hardening at 950-980°, tempering at 135-150°	58-59

[1]	[2]	[3]			[4]	[5]
		[a]	[b]	[c]		
From 50 to 500 thousand pieces	Low Pressure	7	Steel with considerable content of carbon and chromium	2% C; 0.3% Mn; 0.25% Si; 13% Cr; 0.2% V	Oil hardening at 950-980°, tempering at 200°	62-63
	High Pressure	7a	Ibid	Ibid	Oil hardening at 950-980°, tempering at 425°, chrome plating	58-59

: 20 :

[1]   [2]   [3]   [4]   [5]

                [a]   [b]   [c]

                7   Ibid   Ibid   The same as for
                7a   7 and 7a depend-
                                                ing on the need
More than   for reburnishing
500 thousand   and for addition-
        Any   al chrome plat-
pieces Kind   ing

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                8   Hard-alloy
                        metal ceramic
                        linings

Presses

In pressing hydraulic and mechanical (frictional and crank shaft) presses are used. Frictional presses are less favorable, for their use carries the risk of breaking the press mold. The main requirement of presses is that they have a sufficiently large window (the distance between the plunger in its upper position and the lower plate) and stroke for the plunger. The size of the window should be from 4 to 8 times the height of the compact, the stroke 3 1/2 times. Presses are to be preferred which have an upper and lower compression (for ejecting the compact). A hydraulic press of this type is shown in Figure 48. Certain specially designed presses provide not only vertical but also lateral compression. In metalloceramic manufacture presses of both single and double action are used. At the present time there are being built hydraulic presses for briquetting of metal powders with a capacity running up to 5,000 tons, and mechanical (crank shaft and excentric) presses up to 1,500 tons.

Figure 48. Hydraulic Press.

Figure 49. Diagram for Automatic Pressing.

Automatic pressing is most widespread. The manner of operation of an automatic press is shown in Figure 49. The powder mixture, loaded into funnel "a" travels by its own weight into sleeve "b", and ends up over the matrix of press mold "c". When

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the mold is filled up, the sleeve moves back, making room for
the upper die "d" which is to do the pressing. After this the
lower die "e" ejects the product and the sleeve "b" moves for-
ward for the next loading and in the same process pushes off the
table the press product. Automatic pressing may be done both
on hydraulic and on mechanical presses. The productive capacity
of automatic presses reaches several thousand articles an hour.
The problem of automatic pressing is connected not only with the
manufacture of automatic presses, the design of which is not
particularly complex, but also with the mass production of pro-
ducts of a particular size and the use of a strictly standardized
powder (with constant pouring weight and fluidity of powder mixture).
Inasmuch as the installation and regulating of new press molds
on automatic presses takes much time (up to 30 hours), automatic
pressing is not profitable for small-quantity production and
non-standardized powders. Figure 50 shows an automatic press.

The speed of pressing is greater for small and non-complex
items than for large and complex ones.

In non-automatic pressing and loading a brigade of 2-3 persons
(press operator and weigher, or press operator, weigher, and pourer)
can produce on a single press in 8 hours from 400 to 8,000 details,
depending on the size and complexness of the product.

Figure 50. Automatic Press.

In automatic pressing and loading the speed of pressing is
determined by the speed of the press. Thus, the pressing of simple,

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small details on a rotating automatic press of the mechanical
type may be done at a speed of 1,000 strokes per minute. The
speed of pressing of larger and more complex details on hydraulic
presses decreases to 4 strokes a minute. The speed of the stroke
of the plunger on hydraulic presses may attain 750 millimeters
a minute when loaded and 6,000 millimeters when empty.

Diffrent Types of Pressing

Bit ("mundshtuchnoye") pressing is widely used in pro-
cessing cast metals by pressing for obtaining pipes, rods, etc.,
and also in the ceramic and electrode industries for pressing
bricks, pipes, electrodes, etc.

Bit pressing was introduced into the metalloceramic indus-
try as early as at the end of the last century (167) for pro-
ducing osmium wire for use in electric bulbs. In 1903 this method
was applied to the pressing of tunsten. The design of a press
mold for bit pressing of wire (138) is shown in Figure 51. The
pressing operation calls for squeezing across the opening of
the bit a paste obtained by mixing powdered tungsten with water,
a water solution of sugar, dextrin, tragacanth, etc., or even
a cadmium-mercury amalgam (167). In bit pressing, the powder
is compressed by pressure directed at overcoming the friction of
the powder (paste) against the sides of the opening of the bit.
Bit pressing was discontinued in the metalloceramic industry
prior to 1910.

However, bit pressing was resurrected during the years of
the last war, when it was widely used for making pipe sections and

rods of hard alloys. There was recently published a work (166)

dealing with bit pressing of weld rods from 18-8 steel.

Powders from ferro-chromium, silicon, ferro-silicon, nickel,

manganese, and iron are mixed with starch and water and then

pressed across the bit, fashioning continuous rods having a

diameter of 6 millimeters. These are later baked and subjected

to additional processing.

The advantage of bit pressing over ordinary pressing lies

in the possibility of obtaining products of even density with

a very large ratio of length to the transverse cross section

and to the wall thickness.

Figure 51. Diagram of Bit Pressing.

Thereare indications that it is possible to adopt centri-

fugal pressing (194) wherein particles press against the walls of

the press mold through the action of centrifugal force produced

by fast rotation. The advantage of centrifugal force is applied

to each individualparticle, and not to the entire conglomerate,

which makes it possible to eliminate the defects connected with

the friction of the powder against the wall of the press mold.

Gardi (Hardy) recommends the adoption of vacuum pressing of

fine powders with low fluidity. According to him, vacuum pressing

of metal powders is widely used in Europe. However, we were unable

to get any confirmation concerning the industrial application of

this method. The plan of a vacuum press installation as indicated

by Gardi is shown in Figure 52. In Gardi's opinion the vacuum

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method has the following advantages.

Figure 52. Design of Vacuum Press Installation (156).

1 - vacuum pump; 2 - exhaust; 3 - die; 4 - matrix;

5 - porous plug; 6 - manometer; 7 - valve; 8 - vacuum

pipe; 9 - hermetic bunker; 10 - vibrator.

(1) Increase in the fluidity of powder. A copper pader with a 94 percent fraction minus 325 mesh, when tested in air, would not at all pass through a funnel with a 3-millimeter opening. When tested in a vacuum (3 millimeter mercury column), 410 grams passed through per minute. Increase in fluidity is connected with speeding up the loading of the press mold.

(2) A considerably greater density in filling the press mold with powder prior to pressing, which decreases the compression factor.

(3) Up to five times less pressure necessary for achieving the required density in pressing (from 40 kilograms per square millimeter to 8 kilograms per square millimeter). (Such a large decrease in pressure, even though observed by Gardi, seems surprising to us, although a certain amount of decrease in pressure is doubtless possible. Its reasons are explained in Part B of this chapter.)

B. PROCESSES TAKING PLACE DURING PRESSING

Modification of Sturcture

Metallographic and X-ray study of the structure of compacts gives us cortain insight into the processes which take place during cold presing.

In compressing a cast metal the individual crystallites ore produce the deformation of the entire conglomerate and are oriented in the direction of the deformation of the metal. Such an orientated deformation of the granules is connected, as investigation with X-ray has shown, with the texture and a definite predisposition of orientation of the lattices of the crystallites.

A powdered metal in contra distinction to a solid cast metal may be deformed both through the deformation of individual particles and through the mixing of particles in such a way as to fill up the pores. In pressing the height of the briquette decreses 3-4 and more times. However, metallographic experiments carried out by the author (4, 5) on briquettes made from powders with equal-axisparticles did not show any appreciable change in the relation between vertical and transverse cross sections of particles. Figure 53 shows the structure of a copper powder compressed by a pressure of 40 kilograms per squarc millimeter, the particles of which hae the original spherical shape. As can be seen from Figure 58, the pressing did not result in the squashing of the particles in the direction of compression but in a non-oriented deformation at places of mutual contact. As a result the particles preserved their equal-axis

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character while changing from equal-axis spherical particles to equal-axis polyhedral particles. In connection with such a seeming all-sided "contact" type of deformation, briquttes show an absence of the structure indicated by the X-ray investigations of Trzhebyatov-skiy (192).

However, even if the preferred orientation of the lattices is absent, there is observed an orientation of the actual particles due to the unequal sizes of the original particles. Unequal-axis particles

Figure 53. Briquette of Granulated Copper. X 500 (Bal'shin).

even prior to pressing dispose themselves over a wider cross section of the horizontal surface perpendicular to the force of the weight. This preferable orientation is still more intensified by the compressing action of the pressing.

a

b

Figure 54. Compact of Electrolytic Tin with a Relative Density of 80 Percent. a - transverse cross section, X 500; b - the vertical cross section shows the direction of the compression (Bal'shin).

Figure 55. Fractured Pieces of Baked and Compressed Copper Moldings: Fine-grained and Stratified. Direction of Compression X 1 (Bal'shin).

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Figure 54 shows the orientation of compacts of electrolytic tin powder with uneven axes for particles of wide corss section perpendicular to the pressure. Oriented stratification is to be noted both for the large fractured pieces of compacts and sintered products made from powders of flat particles (Figure 55). Such an orientation increases according to the degree of compression. The surface layers of the compacts are also frequently observed to have a "surface" orientation of particles which are disposed with respect to their wide cross section parallel to the surface of the object. This phenomenon is caused by the friction of the powder against the wall of the press mold. It is greater in the transverse cross section than in the direction of the compression because the lateral pressure in a briquette is less than the compression pressure (see Figure 54). The author took a count of particles on vertical and transverse microsections of briquettes of even-axis particles compressed to different densities. The number of particles present per unit of area (and unit of length) increased in proportion to the volumetric density of the compacts. Consequently, the values of "volumetric", "flat", and "linear" density coincide with porosity. They may, of course, be greater for some cross sections than for others, but the average values coincide.

a   b   c

particles   pores

Figure 56. Schematic Drawing of Consolidation in Pressig.
a - 50 percent porosity; b - 25 percent porosity; c - zero porosity.

A schematic drawing was made of consolidation in pressing on the basis of these counts as shown in Figure 56. The schematic drawing shows that the number of vertical layers of particles does not change in pressing, while the transverse layers decrease in proportion to the volume (in inverse proportion to the density of the briquette). The number of layers, both vertical and transverse, does not change per unit of length. However, the number of particles per unit length of layer increases proportionally to volumetric density. The drawing shows that consolidation occurs seemingly by swing particles into empty spaces. This movement of particles is accompanied by displacement in the existing places of contact.

There takes place simultaneously with the displacement an increase in the areas of contact surface (Figure 53). Contact deformation arising in this way must be accompanied by cold-hardening of the particles. The initial consolidating phases of pressing were pointed out by Trzhebyatovskiy (192) on the basis of X-ray studies of briquettes and changes in their hardness during baking. According to Trzhebyatovskiy's findings the Brimel hardness of copper briquettes compressed under a pressure of 300 kilograms per square millimeter reached 180 kilograms per square millimeter, at the same time that the greatest hardness of toughened cast copper was only 130 kilograms per square millimeter.

Figure 57. Distortion of Twinning Planes Occuring in
Pressing Electrolytic Copper at a Pressure of 60 Kilograms
per Square Millimeter. X 500 (153)

Deformation and toughening of particles is localized
principally in the vicinity of the places of contact. With
increase in the density of the briquette, the deformation and
toughening spread both along the surface of and within the par-
ticles. Pressing may be accompanied not only by plastic but
also by brittle deformation expressed in the disintegration of
particle agglutinations into individual particles (Figure 12),
destruction of external protrusions on particles and sometimes
even of the particles themselves (such as in compressing a
brittle cast iron shaving).

Contact Phenomena

Further understanding of the processes of pressing must be
preceded by an acquaintance with certain elementary facts dealing
with contact phenomena.

Contact surface is determined by the size of the parts of
bodies (particles) in contact with each other and by the separations,
the transverse dimensions of which do not exceed the radius of
action of atomic (molecular) forces. Mutual contact existing
between contiguous bodies (particles) may be either direct or
through the film of the admixtures.

Stresses either existing within bodies (particles) or
being exerted by one body (particle) on another can be transmitted

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only through the agency of molecular forces. For this reason,
the definition given above may be replaced by the following
equivalent: <u>A Contact surface is determined by the size of the
areas of surface through which there is transmitted a stress from
one contacting body (particle) to another.</u>

Figure 58. Profile of a "Smooth" Surface of a Particle (Ardenn).

a   b   c

Figure 59. Contact Surface.

a - surface of separation pependicular to pressure;

b and c - not perpendicular to pressure.

Contact points are frequently the principal, and sometimes
the only channels for transmitting energy and diffusing different
processes from one body (particle) to another. Thus, the trans-
fer of electrical current from one conductor to another generally
takes place at the points of contact; heat is transmitted from
one body to another more effectively through contact points.
The processes of chemical reaction and diffusion spread among
solid bodies primarily and sometimes exclusively through direct
contact.

The surface of solid bodies, even where polished to mirror-
like luster, are characterized by a certain roughness, capillaries,
and microscopic or submicroscopic cracks. Figure 58 shows the
uneven profile of the surface of a powder particle magnified
many times.

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Thanks to this roughness contact between contiguous solid bodies is possible in the absence of external pressure only in isolated points.

Let us assume that two bodies being subjected to pressure P normal to the surface of separation are touching each other through protruding points (Figure 59). Let us further suppose that the boundary between the contact areas coincides exactly with the surface of separation for the contiguous bodies, i.e., it is normal to the pressure being applied (Figure 59). Where the surface A of these contact area is very small, while force P is large, then the actual specific pressure on the contact sectors $\frac{P}{A}$ exceeds the critical stress σ_c and thus there begins a plastic yield on the part of the material. The increase in contact surface resulting from such plastic deformation will continue to that moment when the stress in the contact areas decreases below the critical value σ_c. With respect to this the size of contact surface is determined by the formula

$$\sigma_c = \frac{P}{A} \qquad (10)$$

or

$$A = \sigma_c P \qquad (10a)$$

i. e., if σ_c is equal to a constant, then the size of contact surface is proportional to the outside pressure.

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Actually, the contact surface almost never coincides with the surface of separation (Figure 59 b and c). It is not difficult to understand that the yield point of contact protrusions does not depend on the profile and actual size of the contact surface but only by their transverse cross section, i. e., on the magnitude of A_H of the projection of contact surface on the surface of separation normal to the pressure being applied. In which case

$$\sigma_c = \frac{P}{A_H} \tag{11}$$

or

$$A_H = \sigma_c \, P \tag{11a}$$

In the future we shall almost always be dealing with this projection of contact surface on a surface normal to the acting force A_μ. It would be much more correct for brevity's sake to introduce for the term A_H a special expression, such as "nominal contact surface".

More appropriate terms would be "contact section" or "area of contact section" inasmuch as this projection is equal to the section of contact protrusions normal to the acting force. We shall also make use of the expressions "contact surface" and "size of contact surface" with the understanding that they do not refer to the actual surface but to the projected surface.

Non-reversible deformations of sectors may be in a number of cases not only plastic but also brittle. For example,

a piece of coal or chalk under the action of its own weight leaves
a mark on paper due to the breaking off of particles of the
material at the places of contact. Formula (11) would con-
tinue to hold true even in the case where by σ_c is meant
a critical yield point the exceeding of which causes protru-
sions to continue breaking off until there are formed support-
ing areas of a size large enough to cause the pressure per unit
of area of the contact projection to decrease below the cri-
tical value σ_c .

The value of the critical stress σ_c is closely connected
with the hardness of the material. In formula (11) it follows
that σ_c is equal to the pressure necessary to form a contact
surface, the area of projection of which on the surface normal
to the acting force, is equal to one. In determining hardness
according to Brinell, Vickers and Meyer (one can get detailed
information on hardness according to Meyer in O'Neil's book
- 92), the mark made by the pressure of a steel or diamond
ball or cone on the softer metal being tested is essentially
the surface of contact between them. Hardness according to
Brinell and Vickers in this case is equal to the pressure neces-
sary for forming a unit of area (1 square millimeter) of the
surface of contact with the experimented metal, while hardness
according to Meyer is equal to the pressure in kilograms being
exerted on the created contact sector having an area of projec-
tion equal to 1 square millimeter. In this way the critical
pressure expressed in kilograms per square millimeter coincides
with the hardness of the material according to Meyer. Hardness
according to Meyer is usually a little greater than hardness

according to Brinell or Vickers (by 5-20 percent). In compressing
powders we generally have to deal with the contact of bodies
(particles) of identical and not different hardness as in deter-
mining hardnesses. However, we can assume even from these theore-
tical considerations that the projection of contact surface of
the test body on another of more or less identical hardness does
not have to essentially depend on the hardness of the latter and
is determined by the value σ_c of the tested material and the
pressure being applied. This supposition is confirmed by data ob-
tained by a number of investigators in measuring the surface of
contact between similar metals. Table 7 (160) shows that in
such a case the critical stress does not differ to any signi-
ficant extent from Brinell hardness.

Table 7.

VALUE OF CRITICAL STRESS   (133)

Metal	Load P at Contact in Kilograms	in Kilograms per Square Millimeter	Metal	Load P at Contact in Kilograms	in Kilograms per Square Millimeter
Lead	3	2.3	Gold	15	53
Bismuth	3	3.8	Platinum	15	74
Tin	3	4.5	Nickel tempered	12	83
Antimony	3	10.6	in a vacuum		
Silver	6	31.0	Soft Tantalum	15	90
Copper	6	39.0	Hard Tantalum	15	250
Zinc	3	43.0	Molybdenum	15	169
			Tungsten	21	372

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It should be kept in mind that critical stress σ_t and hardness according to Meyer H_M are not constants of the material independent of pressure but increase with load and deformation as the material becomes toughened. For this reason σ_t in formulas (11) and (11a) increases with pressure while the contact surface grows in proportion to something less than the first power of pressure.

<div align="center">a   b</div>

Figure 60. Contact Surface of a "Single" Layer of Particles.
a - horizontal; b - vertical.

The numerous particles of powder are to be found in many "layers" and "stories". For this reason the relation of the contact surface to the compacting pressure is more complex than in the contact of a pair of bodies. We can consider a free-flowing body as being an association of solid bodies (particles). Let us section a rectangular briquet with a horizontal surface HH being compressed in a press mold by pressure P (Figure 60.).

Surface HH intersects one layer of particles. Let us examine the projection of the surface of contact A_H of this "single" layer of particles together with the other horizontal single layer (the surface of contact is shown in Figure 60 by thick lines). Pressure P is transmitted from one single layer to another in its entirety through the contact sectors. Having considered a free-flowing body to be an association of compact bodies (particles), we can therefore write in accordance with formula (11)

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$$A_H = \frac{1}{\sigma_c} P$$

(12)

where σ_c is the critical pressure being constantly exerted during a certain interval of pressure, A_H is the protection of the contact surface of the horizontal single layer on a horizontal surface. We shall designate value A_H for short as simply the surface of a single horizontal layer or "contact section". This is the area of projection on the horizontal surface HH perpendicular to the compacting pressure of contact points of broken surface being transmitted in its entirety through contact points and pores.

We can similarly consider the projection of the surface of the single vertical layer A'_v on the vertical plane (Figure 60b). Let us note without any derivation that

(13)

where C is a constant coefficient for a known interval,

   ξ' is the relation of the specific pressure on the side walls of the press mold to the specific pressure of compression,

   h is the height of the briquette,

   K is the coefficient, constant for a given pressure interval.

Compression Pressure

Expenditure of pressure in pressing of powder includes

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three factors:

(1) Use of pressure P_1 for compacting the powder in the absence of loss caused by the external friction of particles against the wall of the press mold and with even distribution of pressure and density, over all parts of the briquette. This component of pressure is called net pressure.

(2) Loss of pressure P_2 due to the external friction of particles against the wall of the press mold.

(3) Extra pressure P_3 created by the uneven distribution of pressure and density for the different parts of the briquette.

The sum total of compacting pressure $P = P_1 + P_2 + P_3$ may be called the gross pressure or the full compression pressure.

(a) Net Pressure

For compacts of a small diameter ranging about 10 millimeters and with a height of about 1-3 millimeters both losses from pressure and super pressure are insignificant. The compression pressure is almost equal to net pressure (exceeding it by approximately 5-10 percent).

The behavior of powder bodies under a weight (both in unpressed, pressed, and also baked states) is subject to the following elementary laws.

(1) The same stress directed to a unit of contact section A'_H of a powder body normal to acting force P creates the same

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deformation regardless of the original porosity (density) of the powder metal. This law applies both to elastic and plastic deformations (certain corrections would be necessary in the latter case to compensate for the solidifying of the metal). With respect to deformations of briquettes with a nominal cross section equal to one under the specific pressure P , this law is expressed in differential form as the proportional relation between the increase of stress per unit of contact section and the decrease in the relative volume $d\beta$:

$$d\sigma = \frac{dP}{A'_H} = - K d\beta$$

(14)

where K is a constant coefficient.

(2) The indexes of strength (ultimate stress and yield point) of powder bodies referred to a unit of contact section do not depend (if one takes into account corrections for solidifying the metal) on the degree of porosity and are identical both for very porous and for solid metal. This is expressed by the formula

$$\sigma_c = \frac{P}{A'_H}$$

(15)

where σ_c is the actual tensile strength referred to a unit of contact section A'_H and P is the load.

In pressing the values for σ_c (critical stress or contact tensile strength) coincide with the values for hardness according

to Meyer.

By inserting into formula (14) the term A'_H in accordance with formula (15), we obtain:

$$\frac{d\rho}{\rho} = - \frac{K}{\sigma_c}\, \alpha\beta = - \lambda d\beta \tag{16}$$

where λ , if we do not take into consideration the manifestations of toughening, is a constant value, - the so-called pressure factor.

By integrating the differential equation (16), we obtain

$$\ln \frac{p}{p_1} = \ln p - \ln p_1 = \lambda(\beta_1 - \beta) \tag{17}$$

where ρ and β are the running coordinates, while ρ_1 and β_1 are the coordinates of any particular point on the curve.

Formula (17) shows that decreases in the density of a briquette carried out in an arithmetic progression result in a geometric increase of pressure. It is not hard to see that this relation corresponds to the law of deformation formulated on page 70 (of the original text). In reality, with any initial pressure σ_c the stress per unit of contact section is equal to σ_c . Where the initial pressure is increased n_1 times, the stress per unit of original contact section is equal to $n\sigma_c$. By substituting in formula (17) ρ , in place of the value $n\rho_1$, we obtain:

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$$\tag{18}$$

i. e., an identical stress per unit of contact section
regardless of the values for the original volume of compact ,
and of the original pressure   , creates an identical defor-
mation   .

By converting formula (17) from natural logrithms into
decimal logarithms, we obtain:

$$\tag{19}$$

where $L = 0.434$, and $|$ is the pressure factor, constant for
a certain interval of pressure.

It would have been more convenient to present formula (19)
for a number of cases in the following form:

$$lg\, p = lg\, P_{max} - L\,(\beta - 1)$$

$$\tag{20}$$

where ρ_{max} is a constant equal to the value of the specific
pressure under a condition of 100 percent density for the briquette
(i. e., in a relative volume equal to one).

It should be kept in mind that the contact section is the
smallest of all possible ones and that deformation in pressing has

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essentially an interparticle character.

With 100 percent density for the briquette, the contact section A'_H is equal to the entire area of section of the press mold, i.e., A_H 1. (In deriving formula (20) we decided for simplicity's sake that we were considering a press mold with a cross section equal to one. Under such a condition the compacting pressure is equal to the specific pressure. Should the cross section of the press mold not be equal to one, this would cause no disturbance whatsoever inasmuch as with respect to the specific pressure there would apply that part of the cross section that would be equal to one). In accordance with formula (15)

$$\tag{21}$$

By substituting for and 1 for A'_H, we obtain

$$\tag{22}$$

i. e., the specific pressure required to obtain 100 percent solidity for the compact is equal to the critical contact stress or, what amounts to the same thing, to hardness of the metal powder according to Meyer. As has already been pointed out, hardness according to Meyer differs only to an insignificant extent from the generally known Brinell hardness. By replacing in formula (20) with , we obtain

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Figure 61. Ideal Curve for   (Straight Line).

Figure 62. Actual Curve for   .

In depicting this formula graphically in semi logarithmic
coordinates   we obtain a straight line which crosses the
ordinate   1 at the point   (Figure 61).

Experimental semi lograthimic curves do not coincide with
the theoretical curve (Figure 61). This is to be explained by
the fact that as a result of cold hardening both   and   increase
with the compacting pressure. If one were to draw a tangent
from a point in the curve of Figure 62 having   and   for its
coordinates, it would cross the ordinate   1 at the point
     where   is the critical stress (or, what amounts to
the same thing, hardness according to Meyer), corresponding to
the degrees of hardness of material at a volume   and pressure
    . It is obvious that   during the course of the pressure
changes from the values for hardness of a non-compacted metal to
the hardness of the metal at maximum toughening (where   1),
the so-called pressure of emanation, as per O'Neil.

In Table 8 are given certain values for   computed on

the basis of the author's experimental data on net pressures of different metals. The experiments showed (Table 8) that the size of σ_c corresponds to the hardness of the metal of the powder (microhardness of particles) for the given degree of compact compression.

Table 8.

VALUES OF σ_c FOR POWDERS OF DIFFERENT METALS

[1] Characteristics of Powder	[2] Low Density of Briquette		[3] High Density of Briquette	
	[a] Relative Density of Briquette	[b] σ_c in Kilograms per Square Millimeter	[a] Relative Density of Briquette	[b] σ_c in Kilograms per Square Millimeter
Pulverized Tin, Poured Weight 3.50 grams per cubic centimeter	5⁻6	32	—	—
Fine Electrolytic Copper Poured Weight 0.97 grams per Cubic Centimeter	39	48	95	100

[1]	[2]		[3]	
	[a]	[b]	[a]	[b]
Medium-Fine Electrolytic Copper Poured Weight 1.42 grams per Cubic Centimeter	40	36	93	38
Coarse Electrolytic Copper Poured Weight 2.47 grams per Cubic Centimeter	46	48	93	100
Granulated Copper, Poured Weight 4.50 grams per Cubic Centimeter	—	—	93	85
Annealed Electrolytic Iron Poured Weight 2.70 grams per Cubic Centimeter	46	65	90	78

[1]

[2]

[a]

[b]

[3]

[a]

[b]

Reduced Iron

Poured Weight 0.18 grams

per Cubic Centimeter

Cast Iron Shavings

Reduced Tungsten

Tungsten Carbide

Formula (20), though theoretically very important, is
awkward because of the instability of the coefficients and
constants it contains. The author proposed a formula with more
stable values for the constants:

$$(24)$$

or in the logarithmic formula

$$(25)$$

where ___ is the specific pressure, ___ is the relative volume,
___ the relative density of the briquette, ___ the power ex-
ponent, which is practically constant, for a certain interval
of pressure, p_{max} the specific pressure for 100 percent density,
and ___ the critical stress or hardness according to Meyer.

Logarithm of Specific Pressure
in Kilograms per Square Centimeter

Logarithm of Relative Volume $\log \beta$

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Figure 63. Longarithmic Curve   for Pressing
Electrolytic Copper with a Poured Weight of 1.42 Grams per
Cubic Centimeter (Bal'shin).

With repect to many iron and copper powders the loga-
rithmic curves coincide moreor less with a straight line for
the industrial range of pressures (10-60 kilograms per square
millimeters). Furthermore, the values for   computed
according to the diagram are even in the early stages of com-
pression fairly close to the pressure of emanation of the metal.

(b) Relation of Net Pressure to the Composition of Powder

Formulas (23) and (25) and Table 9 show that the pressure
needed for compressing a powder to 100 percent density is equal
to the highest critical stress for   coinciding with the hardness
according to Meyer of a maximum compacted metal (pressure of
expiration).

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Table 9.

PRESSURE OF EMANATION (92)

[1] Metal	[2] Pressure of Emanation in Kilograms per Square Millimeter	[3] Brinell Hardness of Uncompacted Metal in Kilograms per Square Millimeter	[4] Relation of Pressure of Emanation to Brinell Hardness
Lead			
Tin			
Aluminum			
Silver	80		
Gold	92 - 109		
Copper			
Soft Iron			
Steel Containing 0.28 Percent Carbon			
Tungsten			

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As can be seen from Table 9, the pressure of emanation for hard metals exceeds the hardness of the non-cold hardened metal somewhat more than 1.5 times, for soft metals — approximately 3 times, i. e., with repect to a large degree of deformation, soft metals are toughened more than hard ones.

The pressure necessary for compressing to less than 100 percent density is also determined to a certain extent by the hardness of the metal at the corresponding degree of toughening. One can bring in the idea of equivalent compacting pressures for powders of different metals, but with other characteristics being identical (size and shape of particles, density of the powder pour, distribution and effect of admixtures, etc.). In terms of a very rough first approximation, which may be considered to give primarily an order of relation, these equivalents parallel the Brinell hardness of the metals.

Table 10 gives certain data of the author which show how the specific compacting pressure p , the critical stress σ_c , and the pressure factor of various powders changed with an increase in the relative density of briquettes from 80 to 90 percent.

All these values in the presence of various other characteristics of a powder increase much more rapidly for soft metals.

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Table 10.

RELATION OF ___ AND ___ TO THE RELATIVE DENSITY OF BRIQUETTES

Type of Powder	[1] Poured Weight in Grams per Cubic Centimeter	[2] Relative Density of Compact	[3] Specific Pressure Kilograms per Square Millimeter	Representative Units	[4] Critical Stress Kilograms per Square Millimeter	Representative Units	[5] Factor Representative Units
Electrolytic Tin							
Pulverized Tin							
Pulverixed Lead							
MOZ Copper, Obtained by Reduction from Solution							
Electrolytic Copper							
Electrolytic Iron							

At the first glance the figures given in Table 10 may seem
to be somewhat paradoxical. The pressing temperature (room)
for tin and lead is higher than the temperature of recrystalli-
zation and it would seem for this reason that no toughening
should take place. However, it should be kept in mind that the
temperature of the beginning of recrystallization for metal
powders may be considerably higher than for co pact metals
(Chapter V). Moreover, pressing is done with such speed that no
detoughening has time to take place. It is completely possible
in this way for powders of soft metals to cold-harden faster.
But the fast frowth of pressure and critical stress σ_c with
respect to powders of soft metals can be explained not only by
the cold-hardening of the particles. In great densities a sig-
nificant role is played by "super pressure". While a large part
of a briquette has a relative density ϑ smaller than 100 per-
cent, a small part may have σ_c exceed 100 percent because of
compression from all sides. In this part the local stresses per
unit of contact section are considerably higher than the regular
values for σ_c because of the large size of the modulus of all-
around compression. It is for this reason that the mean values
for σ_c increase so considerably. Super pressure and consequently
the growth of the values for σ_c is higher for soft than hard
metals at high densities.

For this reason, in order to obtain a more exact deter-
mination of pressure equivalents, it is necessary to multiply
the hardness of the metal by a corrective coefficient. If we
take one for the corrective coefficient for hard metals, it
would have to be higher in any case for soft metals, but it is

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hard to determine by how many times inasmuch as the equivalents change with the degree of compacting.

However, it is clear in any case that the pressure equivalents for hard metals are considerably larger than for soft. Thus, the pressure equivalent for tungsten has to be several tens of times higher and for tungsten carbide even more than 100 times higher than either for tin or lead.

It should be pointed out before hand that pressures which are required to make briquettes of the same density from powders of different metals do not by any means guarantee that the briquettes so obtained will be the same as to tensile strength and other characteristics.

Usually solid solutions and intermetallic compounds have a greater hardness than a corresponding mixture of several metals. From the point of view of the technology of pressing it is more practicable for this reason to press a mixture of powders from several metals than an "alloyed" powder of a homogenous hard solution of the same composition. However, from the point of view of the technology of baking (Chapter V) and the final characteristics of finished products, it happens, on the other hand, quite frequently that it is more feasible to use "alloyed" powders.

Oxides have a greater hardness than the corresponding metals. For example (190), the microhardness of a tempered electrolytic iron powder is 52-59 kilograms per square millimeter (compare this with the value of 65 kilograms per square millimeter for σ_z in Table 9 for electrolytic iron), while the

microhardness of incompletely reduced oxides present in iron pow-
der is 350 kilograms per square millimeter. For this reason the
presence of oxides in powders of 10 or more volumetric percent
(Chapter II, page 32 of original text) quite frequently increases
the hardness of particles and the compacting pressure. The in-
fluence of oxides on pressure depends greatly on their origin and
distribution.

According to the author's observation, oxides of incompletely
reduced powders found within particles most significantly increase
pressure. Thus, the critical stress σ_c of incompletely reduced
iron powders (300-450 kilograms per square millimeter) was 3-4 times
greater than for those which had been completely reduced (about 100
kilograms per square millimeter).

At the same time if not too great a degree of oxidation
is retained (up to 0.5-1 percent of oxygen) it does not affect
to any marked extent the values either of critical stress
or of specific pressure σ_c necessary for attaining a required
density. Certain deviations from this values are to be princi-
pally expalined by increase in poured weight and decrease of the
specific weight of the powder in oxidation.

Such a discrepancy in the effect of oxides of different
origin may be explained by the following reasons.

(1) Slight inclusions of oxides within particles of
incompletely restored powders may create an effect which is simi-
lar to dispersion hardening. Solid films of oxides formed on the
surfaces of particles in storing powders which can be broken up

in pressing on the contrary only serve to increase the tensile strength of briquettes to a slight degree.

(2) Incompletely reduced oxides form during the reducing temperature solid solution with the metal. The hardness of particles in such a case may be considerably increased. The formation of solid solutions through oxidation of the metal at room temperature is not probable.

(3) In the opinion of the author, a part of the oxides on the surface of the particles reacts with water vapor and becomes soft and plastic like clay (page 33 of original text). Oxides in such a condition are not harder but even softer than the basic metal and may sometimes help pressing by somewhat decreasing the necessary pressure. (This consideration makes it possible to explain the favorable action of condensed air in press shops where there is a specific humidity in the pressing of such hard powders as tungsten). The transition of intraparticle oxides into a claylike condition is excluded.

The specific weight of oxides is in the majority of cases about 1/3 less than for metals. A briquette of completely oxidized powders with a 100 percent relative density ϑ has about 33 percent porosity after reduction. Moreover, oxidized powders do not solidify as well in baking (Chapter V). Briquettes of oxidized powders for this reason should be compressed to a smaller actual content of pores than for non-oxidized powders. A decrease in porosity of compacts by 1 percent is connected with an increase in pressure of about 5 percent, furthermore, a decrease of porosity in arithmetic progression causes pressure to increase

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in geometric progression. For this reason, in those cases
where oxides do not show any direct effect on pressure increase
in pressing, they may nevertheless increase it indirectly (necessity
for obtaining less porous compacts). Moreover, oxides usually
decrease the properties and standard quality of finished products.
Therefore in practice attempts are made in the direction of
obtaining as low a content of oxides as possible.

(c) Relation of Net Pressure to the Physical
Characteristics of Powders

The physical characteristics of powders (the size and shape
of particles), the volumetric characteristic, and cold-hardening of
particles do not exert a direct effect on the greatest specific
compression pressure necessary for achieving a compression result-
ing in 100 percent density. This maximum pressure is always equi-
valent to the pressure of emanation for materials and depends only
on their composition. This pressure may only indirectly depend
on the physical characters of the original powders to the extent
that they are related to the admixture content.

The effect of physical characteristics on the pressure
which would be required to produce briquettes with a density of
less than 100 percent, on the other hand, is very great. Moreover,
this effect grows with increases in the porosity of briquettes.

The size of particles, in the opinion of the author, exerts
only an indirect effect on pressure. Usually the content of
admixtures (oxides) increases with an increase in the degree of
dispersion, while the poured weight of powder decreases. For this

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reason the pressure necessary for compressing powders to a given
density in the majority of cases increases with powder dispersion.
For those cases where fine and coarse powders of the same metal
have the same admixture content and volumetric characteristic
the pressure remains identical. With respect to dispersed pow-
ders of high poured weight and with an insignificant admixture
content, the compacting pressure may be even lower than that of
coarse powders of the same metal having a lower poured weight.

The effect of the shape of particles is also directly
related to the volumetric characteristic. Powders with smooth
particles (page 40 of original text) have greater density when
poured than rough and curled powders and as a result require
less pressure for attaining a compact of a given density.

Logarithm of Specific
Pressure
in Kilograms per Square Centimeter

Relative Volume - Vo

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Figure 61. Relation of Pressure Diagrams

to Poured Weight of Powder.

1- fine electrolytic copper, poured weight 0.97 grams per cubic
centimeter; medium-fine electrolytic copper, poured weight 1.50
grams per cubic centimeter; 3 - coarse granulated copper, poured
weight 4.50 grams per cubic centimeter.

Figure 65. Diagram of Compression Curves for

Powders of Varying Poured Weight.

Figure 64 shows the semilogarithmic compression curves
$\beta - \log p$ for copper powders of varying poured weight. As can be
seen, the pressures needed for making briquettes of low density
from powders of high poured weight with a high initial poured
density are several times smaller than for the lightest powder.
With further compacting this difference continues to decrease all
the time and finally, when 100 percent density is reached
($\beta = 1$), the pressure becomes approximately the same for all
powders and is equal to the pressure of emanation for copper.
The compression factor increases with increases in poured weight.

Figure 65 shows the diagram of compression curves for two
powders of the same metal but with different poured weights dis-
tributed over the entire field of compression. Under the pressure
caused by its own weight γ , a light powder occupies a poured
volume β_0 , while a heavy powder takes up a considerably smaller
volume β_0' . A pressure of $p_0 \left(p_0 / \gamma \right)$ is required to pack a light

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powder into a volume   . A segment of the ordinate

equal to $\frac{}{}$ shows how many times the pressure is greater for the

lighter powder. In further packing to attain the volume   the

ratio for the light and heavy powders   , as determined by

the segment   of the ordinate decreases   .

For the ordinate corresponding to 100 percent density, both curves

merge and the pressure for both powders is equal to the pressure

of emanation of the metal   .

The net pressure required for compressing a powder to a

certain density is equal to its resistance to compression or in

other words, to its strength at this density. Such a strength

may be conceived of as having two components. One component is

"structural" strength (page 39 of original text) as determined by

the interlocking and strength of surface protrusions of particles.

The other component is the strength of the material making up the

powder which is equal to critical stress   . In case of a

small degree of density for a powder (such as that resulting from

the action of its own weight) the particles interlock only with

the small protrusions distributed over an insignificant part of

their surface, for which reason the resistance of compression

is determined almost exclusively by structural strength. With

further packing, deformation spreads over the width and depth of

particles, while the protrusions are flattened, smoothed out,

and disintegrated. It is for this reason the part of structural

strength decreases with continued increase in the degree of com-

pacting in resistance to compression and results in an increase

on the part of the strength of the material itself.

Finally, when a briquette attains 100 percent density, resistance to compression and to the pressure exerted by pressing does not at all depend on structural strength but is exclusively determined by the strength, i. e., the pressure of emanation of the material itself. (In should be pointed out that in compacting the part played by "structural" strength in offering resistance to compression diminishes, but this does not refer to the "structural" strength of the compact, which, on the contrary, almost always continues to grow. It would be more correct to say that with 100 percent compression structural strength does not disappear but coincides with the strength of the material.) The poured weight of the powder (Chapter II, page 39 of original text) is a direct reflection of its structural strength. This structural strength and initial pressure in pressing are considerably greater for light powders than for heavy ones. But inasmuch as with an increase in density the part played by structural strength decreases, the difference in pressure grows smaller and completely disappears at 100 percent density. The progression of initial differentiation in the strength of light and heavy powders, as determined by the segment of the ordinate $lg\ p - lg\ q$ (Figure 65), may be calculated on the basis of theoretic assumptions. A twofold decrease in poured weight corresponds to an initial increase in strength of several tens of times.

The cold-hardening of particles as conditioned by the method used in fabricating the powder (either by mechnical comminution or processing in a ball mill while mixing the powder composition) increases the hardness of the metal. For this reason it can

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increase the pressure necessary for obtaining briquettes of small density. With increase of density during pressing this effect of cold-hardening the initial powders decreases inasmuch as the action of pressing results in a solidifying of the metal. Finally, the initial hardening plays no part whatsoever in the higher densities of pressing, when critical stress σ_c of the not-yet compacted metal reaches the stage where it is not less than the hardness of the hardened particles. In practice, hardness is quite frequently connected with an increase in poured weight resulting from mechanical processing of powders. For this reason the increase in pressure that it evokes quite frequently overlaps (sometimes even with a surplus) the opposite effect of a decrease in pressure resulting from an increase in poured weight.

A preliminary annealing of cold-hardened powders prior to pressing decreases the hardness of the particles due to softening and restoration of oxides. However, low-temperature annealing is connected with a concomitant decrease in the poured weight of the powder (Chapter V) and for this reason it does not always lower the compacting pressure. High-temperature annealing on the other hand, increases the poured weight and consequently considerably improves compressibility.

(d) Lateral Pressure

Let us imagine for ourselves a briquette which has acquired 100 percent density but which is being subjected to a vertical pressure p_v. It is in the shape of a cube (Figure 66)

whose sides are 1 centimeter long and parallel to the axes of
the coordinates of which the Z-axis is parallel to the pressure.

Figure 66. Diagram for Computing Lateral Pressure.

The pressure compresses the cube vertically (Z-axis) and
expands it horizontally (X- and Y-axes). However, the cube is
surrounded by a body of metal and consequently cannot expand, which
in turn results in lateral stresses.

The transverse expansion in the direction of the X-axis
is proportional to Poisson's coefficient ν and to the vertical
pressure P_v and inversely proportional to elasticity modulus E
i. e., it is equal to $\nu \dfrac{P_v}{E}$. Consequently, the sum total
of expansion along the X-axis is equal to $\dfrac{P_h}{E}$.

However, lateral pressure P_h along the X-axis causes a
compression along the X-axis equal to $\nu \dfrac{P_v}{E}$.

Since the lateral expansion of the cube is a practical
impossibility, the total expansion along the X-axis must equal
the compression along this axis, i.e.,

$$\nu \frac{P_v}{E} + \nu \frac{P_h}{E} = \frac{P_h}{E}$$

(26)

from which

$$\frac{P_h}{P_v} = \xi = \frac{\nu}{1-\nu}$$

(26a)

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The value for   i.e., the relation of the specific
compression pressure to the specific lateral pressure, equal in a
compact briquette to   is called the coefficient of la-
teral pressure.

The relationship existing between   and   may be
represented in the form of

$$ \tag{27} $$

Let us now consider the magnitude of the coefficient of
lateral pressure   and Poisson's coefficient   with respect
to porous briquettes. The metallographic investigations of the au-
thor (page 64 of the original text) showed that the area of a
section occupied by the metal of a porous compact is proportional
to its relative density   . Imagine that the cube as depic-
ted in Figure 66 has a relative density of 60 percent. In such
a case 40 percent of the lateral surface of separation ZY existing
between the cube and the surrounding metal is occupied by pores.
In this part of the surface the cube may expand since lateral
resistance is absent. It is for this reason that the lateral
pressure takes up only 60 percent of the surface of separation taken
up by the metal and is equal to only 60 percent of the lateral
pressure for the entire cube. In any case, according to the opinion
of the author,

$$ \tag{28} $$

where   is the coefficient of lateral pressure for a

porous briquette

is the coefficient of lateral pressure for a solid

metal, and

is the relative density of a briquette (in fractions

of unity).

(Formula "9" gives the true values for lateral pressure only for use with actual values of density and compression pressure at a particular spot of briquette. When using mean values of density and compression pressure, the computed values for the lateral pressure may disagree somewhat with the actual ones.

For example, the values   and   with respect to the walls of the press mold may be 20-40 percent greater than the mean values.)

We can develop formula (9) as shown on page 54 (of the original text) from formulat (28) as follows:

$$ \ldots $$

Poisson's coefficient for a porous compact should be combined with the coefficient of lateral pressure of the same relation as that for a compact metal, i. e.,

$$ \nu = \frac{\xi}{1 + \xi} \tag{29} $$

from which

(30)

Table 5 contained the values for _____, and _____, as computed by the author with the aid of formula (9), for different densities of compacts made from certain metals. The values for Poisson's coefficient for solid metals were based on Landol't-Bernshteyn (135).

It follows from Table 5 that for certain exceptions _____ and _____ decrease with the hardness and refractoriness of a metal. Poisson's coefficient increases when the temperature of the metal is raised. This should be accompanied by an increase in the coefficient of lateral pressure.

Up to now no measurements have been made of lateral pressure in metal compacts. Mes'kin (81) suggests that 30-35 percent of the compacting pressure be used for computing the pressure exerted on the walls of the press mold. Vul'f (Wolf) (194) gives 20-25 percent. These figures do not differ to any marked extent with the figures given in Table 6. For example, the coefficient of lateral pressure is 27 percent for iron powders having a porosity of 30 percent.

By knowing the value of _____, it is possible to compute the strength of a press mold by using Lyam's formula

where   is permissible stress, D the external and d the internal diameter of the press mold. In determining   it is necessary to take into account what is mentioned in the footnote given on page 81 (of the original text).

(e) Loss of Pressure through Friction against the wall of the Press Mold -- Ejection Pressure.

Let us imagine that a compact with a height   and a relative density   is in a cylindrical press mold having a diameter   and is subject to specific pressure   (Figure 67). The total pressure   on the compact is equal to

The pressure on 1 square centimeter of lateral surface of the briquette   may be considered in accordance with formulas (9) and (26) (under conditions where the briquette has small dimensions) as being   where   is the coefficient of lateral pressure for a relative density   of the compact.

The entire lateral surface of the compact is equal to   so that that sum total pressure   on it consists of:

$$P_n = \pi D h \, p_n = \xi \pi D h \, p = \ldots \pi h p = \xi \pi D h p$$

(31)

where   isthe coefficient of lateral pressure when   100

percent,   the adduced height of the compact, i.e., the

height when   equals 100 percent (see page 40 of the original

text).

It follows from formula (31) that the total pressure exerted

on the lateral surface of the compact is equal to the specific

pressure being exerted on the adduced lateral surface of the briquet

and on the coefficient of lateral pressure for a compact metal.

In this way the total lateral pressure is dependent solely on the

compacting pressure and not on the porosity of the briquet.

Loss of pressure due to friction of the powder against the

wall of the press mold   is accordance with the law of

Amontons-Coulomb is equal to

$$(32)$$

where   is the coefficient of friction of the powder against

the wall of the press mold.

It follows from formulas (31) and (32) that

$$(34) \; \sqrt{sic}$$

The relation of loss of pressure   to the total

compacting pressure   is equal to

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$$\Delta P = \frac{\Delta P}{\pi} \cdots = \frac{\pi D h P}{\pi D h} \cdots = \frac{h}{D} \tag{35}$$

Loss of pressure due to friction of the powder against the wall of the press mold may be determined experimentally on the basis of the following considerations. After pressure has been discontinued on the briquette, the lateral pressure continues to have almost the same value for P because the walls of the press mold hinder the expansion of the briquet. For this reason it is necessary to exert force f in order to eject the compact:

$$f < P \leq \Delta P \tag{36}$$

i. e., the (maximum) ejecting pressure is equal to or somewhat less (sometimes by as much as 30 percent) the loss of pressure ΔP.

Figure 67. Diagram for Computing Loss of Pressure Due to Friction.

Figure 68 [sic] shows the results of several experiments of the author in determining ejection pressure in relation to compression pressure when D = const and h = const (all the other experiments gave completely similar results). In such a case all values in formula (35) are constant and $\frac{\Delta P}{D}$ constant must be observed.

Figure 68 [sic] shows that this relationship actually existed and that the ejection pressure (equal or proportional to loss of pressure) was always proportional to the compression pressure regardless of the porosity of the briquette.

These experiments confirm the rule established by the author according to which the coefficient of lateral pressure   is proportional to the reltive density of the briquette   .

The value of the coefficient of friction   for "dry" metal powders without any special admixtures varied in the experiments of the author from 0.28 to 0.20 (the press mold was wiped with a "dry" rag before each pressing). Additions of graphite considerably decreased pressure loss and ejection pressure. The introduction into the mixture of 3 percent graphite usually decreased the coefficient of friction and the ejection pressure by 2-3 times. The introduction of various lubricating agents (stearic acid, oil, glycerine) lowered ejection pressure usually 1.5-3 times. (Dry lubrication — graphite — decreases   without changing the value   . Significant quantities of liquid lubricants can together while decreasing   also increase   . This phenomenon may decrease somewhat the effectiveness of lowering ejection pressure when using liquid lubricants).

The experiments of the uathor in pressing dry powders without such additions showed that the coefficient of friction increased somewhat with the hardness of the metal.

Formulas (31) and (35) are true only for insignificant values of   . In reality, formula (35), for example, can

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apply with accuracy only when the values of   are infinitely

small, i. e.,

$$(37)$$

By integrating this equation we obtain:

$$(28)$$

where P is the pressure exerted by the die,   is the pressure

at the bottom of the briquette at a distance of   from the die,

and   is a constant quantity. The ejection pressure   is

equal to

so that the relation is

Kilograms

Ejection Pressure

Kilograms

Compression Pressure P

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Figure 68. Relation of Ejection Pressure to Compression Pressure.
1 - iron; 2 - iron-graphite; = 20 millimeters. (Bal'shin).

Kilograms

Ejection Pressure

in Millimeters

Figure 69. Relation of Ejection Pressure to Reduced Height .
1 - iron; 2 - iron graphite; = 4000 kilograms per square
centimeter. (Bal'shin).

The quantity approaches where the ratio
is close to unity. With an increase in i. e., with a
loss of pressure, becomes smaller than . For this
reason it follows that with an increase of in formula (38)
the loss of pressure and ejection pressure does not increase
proportionally but less quickly (especially for large values of
).

Figure 69 shows certain curves of the relation of ejection
pressure (loss of pressure) to reduced height , as obtained
by the author. These experiments allow one to make the following
conclusions:

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(1) in the case of a small value for μ (Figure 69, curve 2 for iron-graphite) ejection pressure (loss of pressure) grows proportionally with in accordance with formula (35);

(2) for large values of $\frac{\mu \xi}{}$ (Figure 69, curve 1 - iron powder) ejection pressure (loss of pressure) grows almost according to formula (38), and sometimes even less than by that formula. Such deviations from formula (38) are to be explained by the uneven distribution of pressure and density for the cross section of the compact.

It follows from formular (35) that ejection pressure (loss of pressure) changes in inverse proportion to the size of the diameter D of the compact. In reality ejection pressure drops with an increase in diameter drops to a somewhat lesser degree. This fact is also explained by the uneven distribution of pressure and density along the cross section of the briquette (e).

(e) Uneven Density with Respect to Height
and Cross Sections of Briquettes

Losses of pressure caused by the friction of the powder a ainst the wall of the press mold results in uneven distribution of density both as to height and as to cross section of a briquette.

Loss of pressure due to height is subject to formula (38).

$$\ln \frac{P}{P_h} = \frac{4 \mu \xi}{D} h_\kappa$$

The expression can be replaced by as an approximation where is the loss of relative density by the briquette at a distance of from the die,

is the coefficient of proportionality dependent on the properties of the powder in the same direction as factor and the pressure index .

We obtain from this

$$ $$

(39)

where is constant within a certain range of the coefficient of proportionality.

In this way loss of density with height is proportional to the distance (in given units) from the die.

Grams

Per Cubic

Centimeter

Density

Millimeters

Distance from Upper Die

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Figure 70. Change in Density According to Height of Briquette.
1 - electrolytic copper without graphite, poured weight of 142 grams
per cubic centimeter, one-sided compression; 2 - the same with 4 per-
cent graphite; 3 - the same, without graphite, two-sided compression
(Bal'shin).

Figure 70 shows the results of determining the density of
different sectors of cylindrical briquettes. To make the division
of briquettes into separate sections in relation to height easier,
the powder was poured into the press mold in several weighed
portions which were separated from each other by thin layers of
graphite (4). The experiments showed that in conformance with
formula (39) decrease in density is proportional to the distance
from the die and is subject to the following rules.

(1) Lowering of density decreases with a decrease in the
coefficient of friction   , i. e., with additions of graphite
or lubricating agents (1 1/2-6 times).

(2) Lowering of density with repect to height increases with
the coefficient of lateral pressure   .

(3) Lowering of density with respect to height decreases with
an increase in the index of pressure   (and   change in
one direction).

(4) The drop in density with respect to height decreases with
the diameter of the press mold.

Figure 71. Shape of Sections in a Compressed Cylinder.

(5) Two-sided compression improves considerably the dis-

tribution of density.

Top

Side

Bottom

Figure 72. Distribution of Hardness According to Shor in

a Compressed Copper Cube (Bal'shin).

Figure 71 shows diagrammatically several vertical sections

of a cylinder compressed out of a metal powder with intervening

layers of graphite. The bent shape of the cylinder sections is

explained by the restraining influence of the walls of the press

mold with respect to the movement of the particles. This bending

of the sections increases with the height of the briquette and

the degree of packing. In Figure 55, which shows a stratified

piece of copper concentrate, there can also be clearly seen the

warping of the layers. An inspection of Figure 71 brings one to

the conclusion that the greatest density with respect to the top

section of the cylinder closest to the die is around the edges,

while it is in the center in the case of the bottom layer.

Figure 72 shows the distribution of hardness according to Shor

in a compacted cube, which also confirms this relation.

The uneven distribution of pressure and density cannot be solely explained by the effect of friction against the wall of the press mold. Even where there is no friction, the lateral pressure of the outer parts of the briquette has to be greater than that of the inner ones. This effect increases with the width of a briquette. For this reason ejection pressure decreases somewhat less quickly than in proportion to the diameter of the briquette.

(f) Effect of the Height of briquette on the Compression Curve

With an increase in adduced height h_κ there is an increase in the loss of pressure due to friction against the wall of the press mold. The compression pressure grows in relation to this. The growth of pressure in connection with an increase in h_κ may be expressed by a formula similar to formula (38)

$$\ln \frac{P_\kappa}{P_K} = \frac{4 \mu \xi}{D} h_\kappa + K h_\kappa \tag{40}$$

where P_κ is the pressure necessary for attaining a certain degree of density for a briquette with a given height h_κ ; P_h is the net pressure for attaining that density for a briquette of infinitesimally small height. It follows from formula (39) that the effect of height on the compression curve is expressed in a growth of pressure in a definite proportion (wherein the coefficient of proportionality is the same for any degree of density). This is expressed in logarithmic curves by a displacement of the ordinates of the curve into a segment proportional to h_κ . The angle of the curves (and consequently the values for m and L) should

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not be affected in this respect.

in

Kilograms

per Square

Centimeter

Millimeters

Relative Volume Vo

Figure 73. The Effect of Height on Compression (Bul'shin).

1 - electrolytic copper, poured weight 1.42 grams per cubic centimeter, equals 0.6 millimeters; 2 - the same, equals 4 millimeters; 3 - the same, equals 8 millimeters.

The experiments of the author (Figure 73) showed that such a displacement is to be observed in actuality with but deviations. Such a character for curves of briquettes with different heights also confirms the relation between the coefficient of lateral pressure and the relative density of the briquette as established by the author ( ). When is constant, and do not decrease with the adduced height as shown in the diagram of figure 72.

Millimeters

Adduced Height in

Relation to

Figure 74. Density of Tungsten Briquettes in Relation to Height
when   is Constant (Bal'shin).

It should be pointed out that the maximum density attainable
for a given pressure   is to be observed in the pressing not of
very small quantities but of those with a certain optimum height
for the briquette (Figure 74).

The investigations of the author show that the principal
reason for a decrease in the density of briquetts with heights that
are below optimum isto be found in the difficulty of obtaining
portions with evenly distributed density for very small weights.

In connection with the loss of pressure caused by friction
for tall briquettes the maximum specific pressure for obtaining
100 percent density is always greater than the highest critical
stress.

(g) Effect of the Area of Cross Section of Briquettes
on the Compression Curves

An increase in the diameter of a briquette causes two
contradictory factors to affect the progress of the compression.
On the one hand, an increase in diameter of objects results in
smaller lossof pressure from lateral friction. Such losses are
in inverse proportion to the diameter [formula (35)]. This factor
brings with it a decrease in the pressure necessary for attaining
agiven degree of compression when the diameter of the briquette
is increased.

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On the other hand, an increase in the diameter of a press
mold brings with it an increase in the unevenness of the distri-
bution of pressure and density with respect to the transverse
cross section of the briquette. This unevenness increases with
the degree of packing and calls for a certain "super pressure".
For this reason, with an increase in the diameter of the briquette
there is an increase in modulus λ for semilogarithmic and in
index η for logarithmic compression curves, which may result in
a decrease in the density of the briquette during the higher stages
of compression. The maximum specific compression pressure
for 100 percent density would also be larger in such a case.

(h) "Super Pressure"

It is not difficult to figure out that the compression pres-
sure would have to be greater with uneven distribution of density
than with even distribution. This extra pressure created by
unevenness in the distribution of density we call super pressure.
(Not all unevennesses in the distribution of density result in
super pressure. All uneven density caused by the friction of the
powder against the wall of the press mold is connected with loss
of pressure due to external friction. In contra distinction to
this, super pressure is related to the internal friction of the
powder. However, one cannot speak of loss in connection with in-
ternal friction. Pressure lost through external friction is actually
localized not within the briquette but in the press mold. However,
in the case of internal friction, the entire compacting pressure is
distributed within the briquette and is in nowise lost. Internal

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friction only makes possible the uneven distribution of pressure within the briquette). We have already given above several examples of super pressure. There are to be observed the following cases of uneven distribution of density and the super pressure they cause.

(1) Non-uniform distribution of density with corresponding super pressure caused by uneven filling of powder within the press mold by powder (Figure 74). A decrease in pressure during vacuum compacting (page 62 of original text) should also be attributed to a decrease in super pressure resulting from a greater fluidity of powder and ease of filling. It should be pointed out that difficulties in filling also contribute to a lowering of initial density of the powder within the press mold, and this in its turn increases the compacting pressure.

(2) Non-uniform distribution of density with respect to the cross section of the press mold and the super pressure that it causes. Lateral pressure displaces the particles from the center of the briquette toward the walls of the press mold. In this connection there is to be observed, for briquettes with a small ratio of height to diameter, that the greatest density and pressure is around the periphery and the smallest is in the center of the briquette. Unevenness of distribution of density with respect to the cross section and super pressure both grow with the diameter of the briquette. Losses of pressure from friction are related to the uneven distribution of density not only as to height but also as to cross section (Figures 55, 71, 72). In this connection not only loss of pressure caused by friction but also

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super pressure occurs in tall briquettes. Non-uniform distribution of density with respect to the cross section increases with the degree of compression. Deviation of the compression curve from the theoretical progress and increase of critical stress necessary for 100 percent density, especially for densities of briquettes greater than 80 percent, is to be explained not only by the compacting of the metal but also by super pressure (see page 76 of original text). Super pressure has to increase with the coefficient of lateral pressure ξ, i. e., it must be higher for soft metals (Table 5).

(3) Super pressure in pressing products of complex shape. This problem has not yet been adequately investigated.

Phenomena Observed after Removal of Pressure.
The Elastic Aftereffect

The processes taking place in a briquette after the removal of pressure are very important and are frequently the direct cause of spoilage.

In compacting a briquette the external pressure transmitted through the die is balanced by equal and opposite forces due to forces of internal elasticity. The forces of internal elasticity develop not only in the direction of the pressure but also in all other directions (lateral pressure) balanced by the equal reactions of the side walls of the press mold.

When pressure is removed, these internal forces of elasticity are released so that the briquette under their effect tends to expand

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in every direction. The pressure in the direction of pressing
(longitudinal) is several timesgreater than in the transverse
direction. For this reason the elastic aftereffect is expressed
mostly in the longitudinal direction.

With the removal of pressure the expanion of the briquette
is hindred in the transverse direction by the walls of the press
mold and in the longitudinal by friction against the side walls.
For this reason the action of internal stresses ecomes manifest
principally after ejection or removal of briquettes from molds.
The elastic aftereffect is felt to a certain degree even prior
to removal of the briquette from the press mold.

The elastic aftereffect should be taken into consideration
when designing press molds by allowing for a conelike expansion
of the opening for removing the briquette at an angle of 30
minutes. It is due to the elastic aftereffect that free removal
of bushings is possible from internal cores after they have taken
out of the press mold.

It should be emphasized that the elastic aftereffect creates
not only a reversible elastic difomation but also an irreversible
deformation of briquettes. The elastic aftereffect lowers (but
always only partially) internal stresses. The "compressed"
contact surface of particles caused by compacting decreases
relative to the degree of recovery. The remaining unbroken sur-
face contact — the residual surface — is also "stressed", while
its size in our opinion is proportional to the amount of residual
stresses.

The elastic aftereffect results in a number of cases in breaking of contact among particles over a large expanse and in the formation of so-called laminated cracks (page 105 of original text).

The amount of expansion caused by the elastic aftereffect depends on the first instance on the interaction of two factors — the size of the elastic aftereffect and the strength of briquettes. If the contact among the particles is fast, the absorption of internal stresses is insignificant and expansion is slight. Where the contact among particles is not fast, internal stresses are absorbed to a considerable extent so that expansion is very large.

The expansion of briquettes due to the elastic aftereffect is conditioned by the following considerations.

(1) Expansion in a longitudinal direction is greater than in the transverse direction (usually aproximately 2-3 times). The difference in expansion isparticularly great for powders composed of smooth particles.

(2) Expansion increases from the action of all factors which decrease the strength of contact between the particles. The elastic aftereffect thus is less evident for powders composed of curled and rough particles, from which more durable briquettes can be made, than for powders of smooth or flat particles. Expansion of briquettes increases with the poured weight of the powder.

(3) Expansion increases with the hardness of the metal from which the powders were made. For example, it is larger for tungsten than for copper, and for copper than for tin. In the same way

expansion increases with the cold-hardening of the powder. This tendency is to be explained by two reasons. In the first case, the amount of deformation due to the elastic aftereffect depends on the relation of the size of residual stress in contact sectors, equal to σ_K, to the modulus of elasticity E. The ratio $\frac{\sigma_K}{E}$ is greater for hard metals than for soft. Table 11 shows graphically this relationship. Thus, σ_K for tungsten is 160 times greater than for lead, while the elasticity modulus E is only 23 times larger. For this reason elastic deformation of contact sectors for tungsten is 7.4 times greater. In the second case, the strength of briquettes made from hard metals is attenuated not only because of elastic deformation but also because of the small value of the coefficient of lateral pressure (page 82 of the original text).

(4) Expansion depends relatively little on the compression pressure. Expansion usually has for a fairly large bracket of pressures almost a constant value, which increases somewhat for the very highest and lowest pressures.

For the majority of industrial powders expansion comprises 0.15-0.3 percent of the diameter and up to 0.5 percent of the height of the compact. In the case of inferior powders, expansion amounts to 1 percent horizontally and up to 5 percent vertically.

Table 11.

ELASTIC DEFORMATION FOR CONTACT SECTORS. COMPILED BY THE AUTHOR

ON THE BASIS OF DATA CONTAINED IN TABLE 7 AND OF LANDOLT

BERNSHTEYN (135)

Metal	Critical Stress		Elasticity Modulus		Elastic Deformation for Contact Sectors	
	Kilograms per Cubic Millimeter	Conventional Units	Kilograms per Cubic Millimeter	Conventional Units	Percent	Conventional Units
Lead						
Silver		13.5			39	
Platinum						
Tungsten		6				

Mechanical Properties of Briquettes

(a) Strength of Briquettes

Figure 75 shows a typical compression diagram for a briquette made from copper powder. On the abscissa axis are plotted deformation -- changes in the original length of the briquette , on the ordinate axis deformation loads •

As can be seen from Figure 75 there do not exist any qualitative differences in the deformation curve of a powder briquette from that of a compact metal. A straight lined (or almost straight-lined) segment QA of the curve is to be found, just as for compact metals. If at point A we start to unload our model, we find that the unloading curve coincides with the loading curve. In this way the load creates a "reversible" deformation for such a segment. Within the limits of the straight lined sector the curve is irreversible and a load creates a permanent deformation.

For this reason it is possible to speak of a modulus of "elastic" or "reversible" compression as being similar to the elasticity modulus of a compact metal and of the limits of pro-portionality, elasticity, yield point, and strength for briquettes.

Forexample, the conventional limit of yield for a briquette may be consideredto be that load related to the original area of cross-section at which the deformation diagram deviates from astraight line by 0.2percent of itsoriginal length, i.e.,

$$\sigma_s = \frac{P_s}{f}$$

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The ultimate compressive strength (in the old terminology
-- temporary resistance to compression) corresponds to maximum
load P_{max} related to the original cross section of the briquette
f .

$$\sigma_d = \frac{P_{max}}{f}$$

$$(40)$$

P_{max}

Load   A

Change in Length L

Figure 75. Compression Diagram for a Briquette

In exactly the same way terms which describe residual de-
formations under the action of a load (compression, elongation,
cross-sectional deformation) are quite similar to the terms usually
used in testing materials.

Although there is a certain qualitative resemblance between
briquettes and solid metals, the differences between them, both
quantitative and qualitative, are very great.

First of all, there is a radical differences in the nature
of the cohesion of the grains of a compact cast metal and that
of the powder particles of a briquette. The cohesion of the grains
of a cast metal is due to the engagement between their outer
atoms. In contradistinction to this, the cohesion of the powder

particles of a briquette is not due to such engagement but to the
locking and interweaving of surface protrusions andunevennesses.
The mechanical nature of the strength of briquettes may be illus-
trated by a number of examples.

Data collected by the author shows that the compressive
strength of iron and copper briquettes with particles of different
structure but of identical chemical composition when compacted by
identical pressure differed up to several tens of times (3-5) as
compared to 80-90 percent from changes in compacting pressure. The
ultimate tensile strength foriron briquettes with varying particles
structure varied as much as a hundred times ascompared to 0.03 to
3 percent difference due to variationsin the size of the original
compacting pressure. Furthermore, powders composed of smooth par-
ticleshad the lowest tensile strength and those with bent and
rough particles the highest. When the composition and pressure
are identical the size of contact section and cohesive force
per unit of contact section also are the same. For this reason
differences in strength cannot be explained by cohesion. On the
other hand they can be readily explained by uneven interlocking
and varying elastic aftereffect for particles of different struc-
ture (Table 13).

There is a considerable difference in the strength of bri-
quettes with particles of similar structure butvarying composition.
Thus, the strength of briquettes made of hard metals may be several
tens of times less than the strength of corresponding briquettes
made from soft metals under conditions of identical compacting
pressure. This discrepancy cannot be explained by cohesion because

the smaller area of contact section for metals with a high degree
of hardness is compensated by the correspondingly greater amount
of cohesion per unit of contact section. On the contrary, this
discrepancy in strength can be easily explained by mechanical
reasons, in particular, to the elastic aftereffect which is con-
siderably greater for hard metals (Table 11) and more effectively
decreases the size of contact section and thereby the strength

The ultimate tensile strength of briquettes are many tens
of times below the ultimate compressive strength. If cohesion
determined strength, then there would hardly be more than a differ-
ence of two or three times. This discrepancy can also be easily
explained by mechanical reasons. In compression the surface of
contact and interlocking of particles increase. Therefore, the
ultimate strength in compression is relatively great and when
estimated in terms of unit of contact section it sometimes is
almost as great as for cast metals.

The elongation of powder briquettes is connected to a
decrease in the contact surface and interlocking of particles.
In this connection, the ultimate tensile strength of briquettes
is insignificant, even when computed per unit of contact section
it is tens and hundreds of times less than for cast metals.

The addition of lubricating agents to powders while iso-
lating contact among particles decreases insignificantly and
sometimes actually increases the strength of briquettes. This
factor also confirms the ineffective action of cohesion.

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On the basis of what has been described it may be esti-
mated that the percentage of strength due to cohesion can hardly
be said to exceed 10-20 percent of the total strength of compacts.

Elongation of briquettes by stretching may be estimated to
equal zero. Deformation in compression is also insignificant.
The yield point in compression differs very little from resistance
to compression. Also characteristic for powder briquettes is the
presence of residual stress, equal to σ_K , at the places of
contact of particles ("stress" contact).

The study of the properties of briquettes is worthy of
attention since it is not difficult to understand all the phe-
nomena which occur during compacting and ejection. Moreover, the
properties of finished products depend to a considerable extent on
the properties of the briquettes. During compacting there is
formed a skeleton of powder metal, so that quite frequently the
defects of the skeleton, arising during its formation, cannot be
rectified by subsequent baking.

It has already been pointed out (page 71 of original text)
that the indexes of strength for powder bodies related to a unit
of contact section does not depend (if we do not include corrections
for the toughening of the metal) on the degree of porosity and is
a constant. When applied to the index of strength of powder bri-
quettes (ultimate strength and yield point in tension or compression),
this law may be expressed by the formula

$$\sigma_K = \frac{\sigma}{\alpha} = Const$$

(41)

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where σ is the corresponding index of nominal strength for
briquettes related to their nominal cross section (ultimate strength,
yield point), α is the part occupied in the briquette by the
contact cross section in relation to the nominal cross section, and
σ_K the corresponding index of true strength of briquettes related
to their contact cross section (the true ultimate strength, the true
yield point).

As will be pointed out below in the section "Elastic Pro-
perties of Briquettes", the size of contact cross section may be
determined by measuring the elasticity modules.

The true ultimate strength and yield point for briquettes
in compression correspond approximately to the critical stress,
which almost coincides with the microhardness of the powder particles.
Thus, the true yield point in the compression of copper briquettes
is equal approximately to 40 kilograms per square millimeter, and
in the compression of iron briquettes about 60-100 kilograms per
square millimeter. The ultimate strengths in compression are
close to these figures. The true yield points and ultimate tensile
strengths of briquettes are usually tens of times less than the
same compression.

Tensile Strength	1st Stage	2nd Stage	3rd Stage

Compacting Pressure

Figure 76. Relation of the Strength of
Briquettes to Compacting Pressure.

a   b   c   d   e

Figure 77. Different Types of Disintegration in Briquettes.

True indexes of strength for briquettes related to contact cross section depend neither on porosity nor on pressure. The nominal strength of briquettes increases approximately in proportion to compacting pressure, in conformity with the increase of the contact cross section. By means of a more detailed investigation the relation of nominal strength to pressure may be divided into three stages (Figure 76 and 77).

In the first stage, which corresponds to the lowest compacting pressure, strength grows more rapidly than with the first power of pressure. Characteristic types of disintegration during compression for this stage are disintegration into a formless pile of powder (Figure 77a) or the formation of longitudinal or transverse craks (depending on the direction of aplication of compressing load) (Figures 77b and 77c).

In the second stage, when medium compacting pressures are applied, strength grows proportionally to the pressure. After exceeding the yield point, there are to be observed the appearance of sliding lines at an angle of approximately 30 degrees to the direction of compression. With further compression, the specimens

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fracture along these lines. During the fractures occurring in this stage it is characteristic for there to form cones (pyramids) at an angle of approximately 30 degrees in the direction of deformation (Figure 77d). With radial compression of sleeves and cylinders they break up into four cohesive quadrants (Figure 77e).

In the third stage, when high compacting pressure are being applied, strength does not increase as much as with the first power of pressure. It is characteristic of this stage that so-called laminated cracks form after ejection.

This relation of the strength of briquettes to compacting pressure may be explained in the following way. The strength of briquettes, as has already been said, is primarily a mechanical strength due to the mutual interweaving and interlocking of particles. Such a strength may be called a wedge type strength, if we make use of Gubkin's terminology (35). Electrostatic strength or cohesive strength due to the action of electrical cohesion between the atoms of contact sectors are insignificant. Both types of strength are approximately proportional to the size of contact surface of a "singl" layer of particles which in its turn is proportional to the compacting pressure (page 69 of original text). For this reason the sum total of the strength of briquettes must be proportional to the compacting pressure.

However, there are factors which cause a deviation from a proportional relationship between pressure and strength.

One group of factors accelerates the growth of strength in relation to pressure. Pressure brings an increase not only in

the contact surface of particles but also in the density of bri-
quettes. The skeletal strength of the structure of interlocking
particles, proportional to the first power of pressure, but also
with an increase in the depth of interweaving and interlocking
of particles accompanying growth in the density of the briquette.
This factor assists the growth of strength in being more rapid
than with the first power of compacting pressure. An increase
in pressure and density is accompanied by an increase in the coe-
fficient of lateral pressure ξ (Table 5). For this reason the
lateral pressure P_h shaping the briquette with respect to the
transverse direction grows proportionally not to the first power
of compacting pressure p but to the product of compression
pressure by relative density, i. e., it is to a greater extent than
with the first power of pressure. With the growth of lateral pressure
is accompanied not only by the quick growth of strength but also
a lessening of the difference between strength in vertical and
horizontal directions as show in Table 12.

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with the first power of pressure. With the growth of lateral pressure
is accompanied not only by the quick growth of strength but also
a lessening of the difference between strength in vertical and
horizontal directions as show in Table 12.

Table 12.

RESISTANCE TO COMPRESSION OF ELECTROLYTIC COPPER POWDER HAVING
A POURED WEIGHT OF 2.47 GRAMS PER CUBIC CENTIMETER IN RELATION
TO DENSITY AND COMPACTING PRESSURE

Compacting Pressure (Gross) in Kilograms per Square Millimeter	Relative Density of Briquette in Percent	Resistance to Compression in Kilograms per Square Millimeter		Ratio of Vertical to Horizontal Strength (Anisotropic Coefficient)
		Longitudinally	Transversely	

This group of factors is connected with an increase in the density of the briquette and for this reason is most pronounced in the first stage of low compacting pressure (Figure 76).

Other factors on the other hand decrease the speed of the growth of tensile strength through pressure. In high compacting pressures (Figure 76, third stage) desnity increases most insignificantly and for this reason factors which serve to increase the speed in the growth of strength through press re do not play a marked role. Quite the contrary, there is to be noticed to a significant degree a toughening resulting in a slower growth of contact surface than with the first power of pressure. Toughening also contributes to an increase in the effect of the elastic aftereffect. For this reason there is to be observed during the third stage a smaller growth in strength than with the first power of pressure.

During the second stage of medium compacting pressures the two groups of factors neutralize each other so that there is a linear relationship between nominal strength and pressure.

The difference in the nature of strength of powder briquettes and cast metals is most sharply evident in relation to the effect of composition on strength. Table 13 presents the values for resistance to compression by briquettes of different metals. For possible elimination of the effect of structural factors, powders are compared which were produced by identical methods and which have approximately the same particle structure and relative poured density. There are compared in the first series powders of tin,

copper, and iron obtained through pulverization, in the second
electrolytic tin, copper, and iron powders, and in the third
reduced copper, iron, and tungsten powders.

The results obtained are most characteristic. The strength
of compact cast metals of a given composition grows with hardness,
i. e., tungsten is stronger than iron, iron than copper, and copper
than tin. With respect to powder briquettes there is observed
a diametrically opposite relationship, - strength, expressed both
in absolute figures and in percent with respect to the shaping
pressure, does not increase with hardness but with softness and
plasticity of metal. Briquettes of tin have greater strength
than those of copper, of copper than those of iron, and of iron
more than of tungsten. Such a relationship of nominal strength to
hardness of metal is to be explained by the fact that even when
equivalent compacting pressures are applied creating an identical
size of contact surface, the residual contact surface for hard
metals after removal of pressure and ejection has to be considera-
bly smaller because of the elastic aftereffect.

Table 10 shows that elastic deformation of contact sectors
for hard tungsten is 7.4 greater than for soft lead. It is evident
from Table 13 that expansion after ejection was greater for copper
and iron than for tin (up to 2 times), for iron somewhat greater than
for copper, and for tungsten considerably greater than either
for copper or iron.

Moreover lateral pressure for hard metals, which plays a
very important role in the forming of the strength of briquette

is considerably less than for soft metals. It can be seen from Table 5 that the coefficient of lateral pressure for tungsten is 1.9-2.6 times smaller than for tin, copper, or iron. In this connection not only is the strength of tungsten briquettes 10-15 times smaller than for copper or iron, but there is also a much greater discrepancy between vertical and transverse resistances to compression (Table 13).

[See page 103 for Table 13]

On page 76 (original text) there was considered the question of equivalent pressures in obtaining briquettes of identical relative density from powders of different metals. From what has been said in the present section, there are no equivalent pressures for obtaining briquettes with similar mechanical properties from powders of different metals. Actually there are no pressure which can give an identical elastic aftereffect and coefficient of lateral pressure to both hard and soft metals.

With a considerable content of oxides (5-10 or more volumetric percent), the strength of briquettes is reduced markedly. This is explained by an increase in the hardness of the surface layer of particles and by the simultaneous decrease in their strength due to a diminishing of contact surface and growth of elastic aftereffect accompanying an increase in the quantity of oxides.

An insignificant oxide content affects strength to a much lesser degree. Additions (of liquid and solid lubricants, glycerine, paraffin, stearic acid) to powders for decreasing friction

Table 13.

RELATIONSHIP BETWEEN RESISTANCE TO COMPRESSION, THE METAL
OF A POWDER, AND THE METHOD OF ITS FABRICATION

[1]	[2]	[3]	[4]	[5]	[6] Resistance to Compression				[7]
					Longitudinal		Transverse		
Type of Powder	Kind of Metal	Compacting Pressure in Kilograms per Square Millimeter	Relative Density of Briquette in Percent	Horizontal Expansion during Ejection	Kilograms per Square Millimeter	In Percent due to Pressure	Kilograms per Square Millimeter	In percent due to Pressure	Ratio between Longitudinal and Transverse Strengths (Anisotropic Coefficient)
Obtained by Pulverization	Tin	40	60	0.22	>50	>125	>50	>125	—

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[1]   [2]   [3]   [4]   [5]   [6]   [7]

Relative Density Copper

of Pouring

40-50 Percent.   Iron

Obtained by   Tin

Electrolysis.

Relative Density Copper

of Pouring

15-20 Percent   Iron

Restored Powders. Copper

Relative Density

of Pouring   Iron

12-15 Percent

                 Tungsten

against the walls of a press mold usually only slightly attenuate the strength (decreasing it by 10 percent or less). This is explained by the fact that the strength of briquettes is due to interlocking and not to cohesion, since in the latter case such additions would decrease cohesion by many times.

It is practicable to introduce agglutinating agents (plastics, rubber, etc.) into briquettes only if the powder mixture is composed of very hard powders (carbides of hard alloys).

Briquettes of "alloyed" powders whose individual particles are alloys of several metals are almost always lower in strength than compacts composed of a powder mixture of several metals. This is explained by the fact that solid solutions and intermetallic compounds are harder than the corresponding mixture of metals.

The actual strength of a powder mixture of two metals or of a metal and a non-metal is often lower than the strength computed according to the rule of additivity.

Table 13 also gives one a certain understanding of the relationship existing between the nominal strength of briquettes and the physical properties of the original powders due to the shape of particles and the volumetric characteristic. It can be seen from Table 13 that the strength of briquettes made from heavy powders fabricated by pulverization and possessing rounded smooth particles is considerably smaller than for briquettes made of lighter electrolytic powders composed of dendritic and reduced spongy particles. This is explained by stronger interlocking in briquettes made of powders composed of rough particles. Another

feature might be pointed out here. It is difficult to notice
in the case of soft powders made from tin the effect of the
structure and volumetric characteristic of the powder on strength.
With respect to harder copper the resistance to compression in
the longitudinal direction for briquette's made from pulverized
powders is 2-2.5 times less than for those made from electrolytic
and reduced powders, and with respect to iron, which is even
harder, the difference is even 5-6 times less. Thus the harder
the metal the greater is the effect of structural factors and the
volumetric characteristic. This is to be explained by the fact
that the strength of briquettes made from hard metals is deter-
mined principally by "structural" strength dependent on structural
factors (page 79 of the original text), while for those made from
soft metals are dependent on the strength of the metal from which
the powder is made.

It should also be pointed out that the effect of the shape
of the particles and the volumetric characteristic of powders due
to "structural" strength usually decreases somewhat with density
and compacting pressure. This is explained by the fact that dif-
ference between smooth and rough particles decrease to a consider-
able degree because, on the one hand, of the smoothening out of
the surface of rough particles and the twisting of the profile
of smooth particles during high pressures. One may note a certain
analogy in the leveling out action of compacting and the relation-
ship of compacting pressure to the physical characteristics of
powder (page 77 of original text). However, in contradistinction
to the relationship between compacting pressure and the physical

characteristics of powder, the shape of particles and the structural strength quite frequently exert an effect even in the highest densities of briquettes. Thus, powders with flat particles produce, with very high pressure, briquettes with an insignificant resistance to compression, especially in the transvers direction (resistance to tension, on the other hand, is less longitudinally). This is explained by the unfavorable orientation of particles (Figure 78) with the wide side perpendicular to the pressure, which aids in the formation of laminated transverse cracks.

Figure 78. Copper Briquette with Flat Particles,
Longitudinal Section. X 500 (Balshin)   Direction of Compacting.

a   b

Figure 79. Diagrams of Briquettes from Flat Particles.
a - non-associated; b - associated in conglomerates.

This defect may be corrected by uniting particles in conglomerates. The diagram as shown in Figure 79 explains why, with the association of particles in conglomerates, there disappears the harmful orientation for the wide cross section perpendicular to the compacting pressure.

One can attain such an association in conglomerates, for example, by using agglutinative agents. Figure 80 shows that after the addition to the powder mixture of an agglutinant (rubber in benzine) the harmful orientation of copper particles (Figure 78) disappears. There is to be observed in its place a disorderly swirling of particles into glued-together clumps (Figure 80).

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An even more favorable effect can be achieved by the association of particles in clumps, 0.1-5 millimeters in size, during high-temperature heating.

Formerly, the majority of investigators believed that small particles give greater strength to briquettes because the total contact surface is inversely proportional to the size of the diameter of the particles. Such a point of view has been stated by Sauerwald (184), Rakovskiy (99), and many others.

Figure 80. Copper Briquette with an Agglutinant, Vertical Cut. X 500. Direction of Compacting (Bal'shin).

Kilograms

Resistance to Compression

Millimeters

Size of Grit

Figure 81. Relationship of Briquette Strength to Size of Original Iron Grit (Bal'shin).

However, although the total surface of contact for all particles grows in inverse proportion to their diameter, the contact surface of a single layer (page 69 of original text) serving to determine the strength of briquettes does not depend on the dis-

persion of the powder but only on the compacting pressure. The
investigations of the author showed that the size of particles
exercises in the majority of cases only an indirect effect on
strength. Where, with a decrease in dispersion, there was an in-
crease in poured weight, the strength dropped. However if with a
decrease in dispersion the poured weight did not change or even
decreased, then strength increased. Thus, briquettes of small par-
ticles of vorticity mill-pulverized iron had less strength than bri-
quettes of large particles. Figure 81 gives data on the strength
of briquettes made from reduced iron grit in relation to the size
of the pieces. The poured weight of all the sizes of the grit was
the same (1.4 grams per cubic centimeter), while the density of
briquettes made from particles of varying size compressed at the
same pressure (40 kilograms per square millimeter) differed only
within the range of precision of measurement (by plus or minus 0.3
percent). It is clearly seen that with the exception of the finest
particles (less than 0.1 millimeter in size) strength grows with
the size of grit.

Figure 82. Diagram of the Effect of Geometric Factors on the
Tendency of Briquettes to Fracture.

A - fine powders; strong possibility of forming interparticle
cracks 1 and 2. B - coarse powders; geometric factors hinder
the formation of cracks between particles (Bal'shin).

An explanation for the growth of strength with the size of
particles was given by the author a long time ago (4). From a purely
geometric point of view, largeness of particles helps in attaining

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briquettes possessing high strength (see drawing, Figure 82). Bri-
quettes always disintegrate with the formation of interparticle
cracks. Such cracks are usually greater than the diameter of the
particles. Where the size of particles for one briquette is ten
times larger than for another, the diameter of the cracks must also
be that many times larger. This is why the formation of interpar-
ticle cracks is easier with small particles (Figure 82A), and much
more difficult for large particles (Figure 82B).

Cold-hardening of a powder causes a briquette to have less
strength. The reasons for this can be understood from what has
been said earlier regarding the effect of hardness of metal (page
96 of original text).

The obtaining of durable briquettes is aided by almost all
the factors that contribute to the distribution of density and pres-
sure, such as a careful pouring of powder into a press mold, two-
sided pressing, cleaning and lubrication of the walls of the press
mold, perfectly vertical installation of the die and matrix, etc.,
in the same way as by the favorable action of those factors that
decrease the possibility of damaging the briquette when it is being
removed from the mold, such as by designing the ejecting end of the
matrix with a conical flare at an angle of 30 minutes in relation
to the axis of pressure, etc.

Many specialists such as Rostarchuk (105) and others (134,
154, 146) attach very serious significance to the effect of air on
the obtaining of durable compacts not inclined to crack. In their
opinion, the inclusion of air in briquettes is detrimental to their
durability and may even lead to cracking.

Metal powders are compressed at a pressure in the order of 4,000 kilograms per square centimeter. The volume of pores as a result of this decreases usually 5-8 times. For this reason it is not probable for locked-air to remain at a pressure exceeding 8 atmospheres. Such a pressure should not cause cracking.

Elastic stresses, however, expand the briquette immeasurably more than pressure caused by locked-in air, more precisely by $\frac{4,000}{8}$ or 500 times.

One may thereby assume that air does not play an active role in the cracking of briquettes. Such an active role belongs to expanding stresses which are absorbed during the process of the elastic aftereffect.

But if air is not an immediate factor causing cracking, it still plays a passive role as a factor which indirectly aids in weakening the briquette possibly quite considerably, for fine powders with low permeability and fluidity. As Gardi (Guardi) points out (156), air may decrease the fluidity of powders. A decrease in the fluidity is connected with uneven distribution of density, super pressure, and a corresponding increase in residual stresses. All these factors help to decrease durability and increase cracking in briquettes. The air in hindering pouring may also lower the initial density of packing the powder in the press mold. And this in its turn (page 78 of original text) increases compacting pressure and the expanding stresses related to it and thus helps weaken the strength of briquettes.

For this reason the clearance between the die and the matrix must have enough space for the free exit of air. In no case should

there be used a sliding setting of the die.

In laboratory experiments the rate of compression may be studied independent of the speed of pouring or ejection. In industrial practice an increase in the speed of pressing almost always is tied to an increase in the speed of pouring and the speed of ejection.

An increase in the speed of pouring may sometimes impair to a certain degree evenness in the distribution of powder in the press mold especially when the powder exhibits low fluidity and there are large quantities and a complex shape to the briquette. In this way excessive speed of pouring may have an unfavorable effect on the strength of a briquette.

Figure 83. The effect of Stopping during the Ejection Process
on the Formation of Cracks.

An increase in the speed of ejection, on the other hand, exercises a favorable action. The expansion of briquettes during ejection due to the elastic aftereffect does not take place immediately but at the end of an interval of time. With slow ejection, especially when there are halts during the ejection process, the expansion of the part that has been ejected, as shown schematically in Figure 83 to an exaggerated degree, may result in the appearance of ring-like cracks at the boundary between the ejected and not yet ejected parts.

With fast ejection, cracks cannot form inasmuch as the briquette will expand only after its complete delivery from the press mold.

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The speed of the pressing process (5) does not exercise any significant effect on the strength of briquettes.

[See page 114 for Table 14]

Table 14 presents Shpagin's data (131) showing a certain amount of increase in strength and density with an increase in the speed of pressing.

(b) Elstic Properties of Briquettes

If the elasticity modulus of a briquette is taken with reference to its contact section, its size will coincide with the value for the elasticity modulus for the corresponding compact metal. However, the elasticity modulus for a briquette when referred to its nominal cross section, will be proportional to the size of its contact cross section. This rule is expressed by the formula

$$E' = \propto E$$

(42)

where E' is the nominal elasticity modulus for the briquette, E the elasticity modulus for the corresponding compact metal, $\propto$ the part occupied in the briquette by the contact cross section with relation to the nominal cross section.

Formula (42) makes it possible once we know the elasticity modulus for the briquette to determine the size of its contact cross section.

Inasmuch as the size of the contact cross section is almost

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Table 14.

THE EFFECT OF THE SPEED OF PRESSING ON THE QUALITY OF BRIQUETTES MADE

OF 50 PERCENT COPPER AND 50 PERCENT GRAPHITE

(PRESSURE OF 20 KILOGRAMS PER SQUARE MILLIMETER ACCORDING TO SHPAGIN [131]).

Pressing Time	Density in grams per Cubic Centimeter	Hardness According to Shor	Resistance to Compression in Kilograms per Square Millimeter
20 minutes	3.07	13	0.0
8 "	3.07	13	0.5
4 "	3.08	13.3	0.6
50 seconds	3.09	17	0.6
15 "	3.10	17	0.7
10 "	3.13	17	0.5

proportional to the compacting pressure, then the values for the nominal modulus of elasticity of briquettes made from a given powder would also be almost proportional to the compacting pressure (5).

(c) Hardness of Briquettes

Figure 84 shows the figures of a number of authors on the relation between Brinell hardness and compacting pressure. As can be seen from the curves, with low pressures, hardness grows almost proportionally to the first power of pressure and sometimes even more. With high pressures hardness increases considerably less than with the first power of pressure. There is thus obtained a relation of the same type as for strength (Figure 76). However, hardness deviates from proportional relationship to a greater degree even with lower pressure than does strength. The reasons for this deviation may be explained by the following reasons.

Kilograms

per Square

Millimeter

hardness per

P   Square Centimeter

Figure 84. Relationship of Brinell Hardness to Compacting Pressure. 1, 3 - according to Trzebyatovskiy, 2 - Gettsel', 4 - Kiefer and Gotop.

(1) All the investigators (Figure 84) determined density for the upper surface of the briquette closer to the die and possessing relatively greater strength and density. The values for strength

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nominal modulus of elasticity of briquettes made from a given pow-
der would also be almost proportional to the compacting pressure (5).

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hardness deviates from proportional relationship to a greater degree
even with lower pressure than does strength. The reasons for this
deviation may be explained by the following reasons.

Kilograms

per Square

Millimeter

hardness per

P   Square Centimeter

Figure 84. Relationship of Brinell Hardness to Compacting Pressure.
1, 3 - according to Trzhebyatovskiy, 2 - Gettsel', 4 - Kiefer and Gotop.

(1) All the investigators (Figure 84) determined density for
the upper surface of the briquette closer to the die and possessing
relatively greater strength and density. The values for strength

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were determined (depending on the direction of compression) either by the average strength of the entire volume or by the strength of a weaker and less dense cross section. For this reason solidification at high pressure is reflected to a large extent in hardness than in strength.

(2) In determining brinell hardness for a loose briquette, the work of impressing the ball boils down to a displacement of the deformed volume of metal and to a supplementary packing and solidifying the particles of the powder. Such a supplementary packing increases the hardness of loose briquettes. For a solid briquette the work of impressing the ball involves only in displacing the deformed volume. This factor decreases the speed of growth of hardness during pressure.

The hardness of briquettes is subject to the following laws.

(1) Hardness increases with compacting pressure, density, and strength of briquettes. Where residual contact surface is equal to 100 percent, hardness according to brinell must have a value of one order with net compacting pressure, while with 100 percent density for the briquette it is equal to the critical stress of the material. Hardness decreases very much with a decrease in the size of residual surface caused by the elastic aftereffect. For this reason under conditions of identical compacting pressure hardness of briquettes increases usually not with an increase but with a decrease in the hardness of the metal of the original powder. Hardness also depends considerably on the content of admixtures.

(2) Hardness is anisotropic. It is less horizontally than vertically. This is especially noticeable for hardness according

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to Shor (Figure 72). Such anisotropism may be explained by the fact that the molding pressure in a longitudinal direction is greater while the cross section of particles and porosity is smaller /than in a transverse direction/.

(3) Hardness, corresponding to uneven density, varies for different parts of the briquette (Figure 72).

Electrical Conductivity of Briquettes

Table 15 presents data (165) on electrical conductivity of powders from different metals, compressed at a pressure of 25 kilograms per square millimeter. In connection with the very high resistance of hard metals, one can conclude from Table 15 that a purely metallic contact between their particles is insignificant. The resistance of briquette from very soft metals (tin) is relatively close to the resistance of the solid metal.

[See page 118 for Table 15]

Spoilage in Pressing

One of the more serious forms of spoilage in pressing is that caused by cracks, transverse or diagonal.

Spoilage in pressing is due to one of the following factors (or their combination):

1. Improper design of and defects in press molds.
2. Improper pressing and ejection procedures.
3. Poor quality of powders.

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Table 15.

ELECTRICAL RESISTANCE OF COMPACTED POWDERS (165)

Metal of Powder	Relation of Resistance of Briquette to Resistance of Solid Metal	Metal of Powder	Relation of Resistance of Briquette to Resistance of Solid Metal
Tin		Copper	
Lead		Platinum	
Graphite		Hard Nickel	
Zinc		Tempered Nickel	
Gold		Iron	
Bismuth		Tungsten	
Antimony			

The formation of cracks is most frequently due to improper design of and defects in press molds.

With respect to non-dismantling press molds, their defects cause the appearance of laminated cracks in ejection. In order to forestall the appearance of such ringlike laminated cracks, there should be provided a conical flare for the ejection opening of the press mold (at an angle of 0.5-1 degree, see drawing of Figure 83). Cracking is also assisted by unevennesses in the walls of the press mold due to poor manufacture or wear.

With respect to dismantling press molds the shifting of the wall in pressing or removal of briquette as a result of improper design or assembly of the press mold causes briquettes to crumble with the formation of diagonal cracks. In the majority of cases such shifts occur during high compacting pressures. In this manner diagonal cracks are often due to the joint action of these two factors.

Excessive compacting pressures also assist in the formation of transverse laminated cracks in non-dismantling press molds. Elastic forces, which cause the cracks to form, increase always proportionally to the compacting pressure. The strength of briquettes resisting their cracking increases less rapidly (Figure 76). For this reason at a certain intensity of pressure the rupturing forces of elasticity overcome the strength of briquettes and cause the appearance of laminated cracks.

An excessively slow removal of the briquette, particularly if there is an interruption during this operation, helps in the formation of laminated cracks (diagram, Figure 83).

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The appearance of layers is assisted by all those factors which decrease the strength of compacts (smooth, flat particles, high poured weight, oxidation of powders, inclusion of graphite in powder mixture, cold-hardening of particles, etc.). Powders with large particles are less susceptible to lamination than powders with small particles (Figure 81 and 82).

Pressing Operation

In pressing, work is being done in opposition to the forces of cohesion. This work may be computed on the basis of formula (25). The work of pressing a unit of a given volume, i. e., 1 cubic centimeter of a compact material, that is, given work is expressed by the formula

$$ \tag{43} $$

where is the specific pressure necessary for compacting a material up to 100 percent density, the index of pressing in formula (25), a constant depending on the properties of the powder (varies between 3 and 5 in the majority of cases), and the specific compacting pressure.

$$ \tag{44} $$

If the values and in formulas (43) and (44) are given in kilograms per square centimeter, than the adduced specific work is expressed in kilogram-centimeter per cubic centimeter.

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Where work is expended only in compacting a powder and loss
due to friction of the powder against the wall of the press mold
may be omitted, than value $P_{m s p}$ in formulas (43) and (44) may be
replaced by $\mathfrak{S}_{K\,max}$.

The specific work of pressing ω , i. e., the work of pres-
sing an amount of powder having during the given vinal pressure and
density a volume of 1 cubic centimeter can be expressed by the formula

$$\omega = \frac{\mathcal{P}}{m-1} \tag{45}$$

If one were to add up the adduced work of compacting for
copper under practical conditions of pressing (specific pressure
1,000-6,000 kilograms per 2.5-7), then there would be obtained va-
lues from 3.3 to 45 kilogram-meters per cubic centimeter. Conver-
ting this work into heat, we find that it corresponds many times
less energy than what is imparted to the briquette in baking. The
The sintering temperature for copper is usually 700-850 degrees).